9669WO D1 X

(19) **Europäisches Patentamt**
European Patent Office
Office européen des brevets

(11) Publication number: **0 521 440 A2**

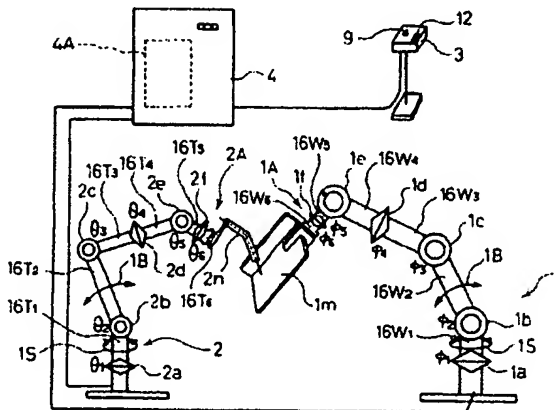(12) **EUROPEAN PATENT APPLICATION**

(72) Inventor: **Kasagami, Fumio**
4-863, Ichibu-cho
Ikoma, Nara(JP)
Inventor: **Kugumiya, Seisuke**
1-742, Oaza-Kitsuki
Kitsuki, Oita(JP)

(74) Representative: **KUHNEN, WACKER &**
PARTNER
Alois-Steinecker-Strasse 22 Postfach 1553
W-8050 Freising(DE)

(54) **A manual teaching control device for operations in an industrial robots-system.**

(57) According to a control teaching device, position and attitude of tool (2n) on tool handling robot (2) can be taught by means of manual operations, being subjected to the movement of position and attitude of workpiece (1m) on workpiece handling robot (1), so that relative position and attitude of tool (2n) against workpiece (1m) can be kept constant. Position and attitude of workpiece handling robot (1) and tool handling robot (2) are computed by use of "actuating signals" of a teaching key means (12) and a "co-acting signal" of a selecting means for sole-action/co-action (9) . Then, joint variables of workpiece handling robot (1) and tool handling robot (2) are calculated. Actuating values for actuators (17W, 17T) of workpiece handling robot (1) and tool handling robot (2) are synchronously outputted after the lapse of time comes into a predetermined infinitesimal time ΔT, therefore, tool (2n) is synchronously co-acted with workpiece (1m).

F I G. 1

EP 0 521 440 A2

TECHNICAL FIELD OF THE INVENTION

The present invention related to a teaching control device for manual operation in an industrial-robots, more particularly, to an industrial robot-equipment enables to be taught by manual teaching operation, which is provided with a workpiece handling robot that is capable to change "position and attitude" of workpiece held in an end effector, such as a robot hand etc. and a tool handling robot that is capable to change "position and attitude" of tool processing said workpiece.

BACKGROUND OF THE PRIOR ART

The industrial-robots composed of a workpiece handling robot and a tool handling robot provided with a tool, such as a machining tool, a welding torch or a welding gun etc., are generally controlled with co-operation by means of method of teaching playback so as to replay movement of both robots at the same time in real processing operations.

Teaching operations for the robot have to be performed before real processing operations. Teach working for both robots are subjected to sole-acting manual operation respectively.

Referring to Fig. 24(a) of the prior art, first, desired positioning for each robot are independently achieved by means of separating movement of workpiece 1m on the workpiece handling robot 1 from movement of tool 2n on the tool handling robot 2. The point of A in the "position and attitude", which are established by the above-mentioned independent movement, is taught as a teaching point of the first positioning. This means that the data of "position and attitude" of tool 2n against workpiece 1m at the point A and the data of "joint variables" of workpiece handling robot 1 are memorized in a computer.

Thereafter, tool 2n and workpiece 1m have to be moved according to commands of an operator in order to obtain the second positioning. When the workpiece 1m is moved by means of movement of workpiece handling robot only as shown by a broken line after teaching point A of the first positioning, the workpiece 1m often contacts with or collides the tool 2n. Therefore, it is necessary to avoid the interference of workpiece 1m with tool 2n each other.

An operator needs to command once retiring tool 2n from workpiece 1m as shown in Fig. 24(b), after teaching point A at the first positioning.

Next, the workpiece 1m is moved to the direction of an arrow 1p by means of movement of workpiece handling robot 1 as shown in Fig. 24(c) in order to obtain a desired position for a next teaching point B. As shown in Fig. 24(d), the point B is taught at the second positioning which is established by means of returning tool 2n to workpiece 1m according to movement of tool handling robot 2.

It is very inconvenient to retire the tool from the workpiece in the middle of teaching operations as mentioned above. Especially, teaching many points forces increase of the number of times for retiring the tool from the workpiece. As a result, it takes a lot of time in order to retire the tool and to return it, causing a problem that the teaching time is, on the whole, prolonged.

Futhermore, an operator often loses sight of a desired next teaching point on the workpiece, when the distance between a teaching point and a next one is short or when an arrangement of a series of teaching points is complicated.

The first objects of this invention is to enable subjecting tool on tool handing robot to movement of workpiece on workpiece handling robot by means of co-acting each other, when an operator teaches both of robots by manual operations.

The second object is to realize exactly maintaining previous position and attitude of tool against workpiece without retiring tool from workpiece one by one during teaching operations.

The third object is to present a teaching control device for simplified manual teaching operations in an industrial robots-system which teaching operations can be rapidly performed by means of accurately subjecting tool to movement of workpiece.

SUMMARY OF THE INVENTION

The present invention is relates to an industrial robots-system taught by means of manual teaching operations, which is provided with a workpiece handling robot that is capable to change "position and attitude" of a workpiece and a tool handling robot that is capable to change "position and attitude" of a tool for processing said workpiece, and composing;

a selecting means for sole-action/co-action enables to select sole-acting manual operation that facilitates changing position and attitude of workpiece on workpiece handling robot and changing position and attitude of tool on tool handling robot separately, or to select co-acting manual operation that facilitates

2

changing position and attitude of tool on tool handling robot by means of co-acting with changing position and attitude of workpiece on workpiece handling robot so that position and attitude of the tool against workpiece can be always kept constant.

a teaching key means outputs actuating signals for changing position and attitude of workpiece.

a control means for manual teaching operations carries out control according to process mentioned after by means of receiving actuating signals from said teaching key means and a co-acting signal from said selecting means for sole-action/co-action, and

said control means for manual teaching operations is a computer carries out controlling function, including;

the first process consists of picking up actuating signals, and computing position and attitude of workpiece handling robot at the starting time of manual teaching operations and position and attitude of tool against workpiece at the starting time of manual teaching operations,

the second process consists of commanding to carry out the third process by means of estimating the state after a preset infinitesimal time when actuating signals in the first process are maintained, and commanding to return to the first process when actuating signals have already changed into different ones, and commanding to terminate teaching operations when all of actuating signals have already vanished,

the third process consists of not only calculating position and attitude of workpiece handling robot but previously calculating position and attitude of tool handling robot by use of position and attitude of tool against workpiece at the starting time of manual teaching operations, which were calculated at the first process, and position and attitude of workpiece handling robot at the starting time of manual teaching operations, which were calculated at the first process,

the fourth process consists of not only calculating joint variables of workpiece handling robot by use of position and attitude of workpiece handling robot which were calculated at the third process but calculating joint variables of tool handling robot by use of position and attitude of tool handling robot which were calculated at the third process,

the fifth process consists of not only previously calculating actuating values for actuators of workpiece handling robot by use of joint variables of workpiece handling robot which were calculated at the fourth process but to previously calculating actuating values for actuators of tool handling robot by use of joint variables of tool handling robot which were calculated at the fourth process, in addition, including not only to synchronously output signals of actuating values for actuators of workpiece handling robot and signals of actuating values for actuators of tool handling robot just after an infinitesimal time, but to command repeating on and after the second process.

Said actuating signals of the teaching key means may be adopted the signals commanding translation along each axis or rotation around each axis in the cartesian coordinates of position and attitude of workpiece handling robot. And said actuating signals of the teaching key means may be also adopted the signals commanding motions of joints of workpiece handling robot.

According to the present invention, even if position and attitude of workpiece is changed in order to teach a next teaching point from one teaching point, the movement of tool handling robot can be acculately subjected to that of workpiece handling robot by means of co-acting each other so that position and attitude of tool against workpiece at the starting time of manual teaching operations can be always kept constant. As a result, it becomes unnecessary to retire the tool from the workpiece in order to avoid interference each other, when the workpiece is moved to desired positions. An operator is able to catch the last teaching point even when a next point is taught in the state that position and attitude of workpiece have already been changed, therefore, enabling rapid and exact teaching of other next points.

BRIEF DESCRIPTION OF DRAWINGS

Fig. 1 is a schematic drawing of a teaching control device and a teach pendant in an industrial robots-system composing a workpiece handling robot and a tool handling robot.

Fig. 2 is a schematic drawing of a workpiece handling robot of 6 degrees of freedom which holds a workpiece in an end effector.

Fig. 3 is a schematic drawing of a tool handling robot of 6 degrees of freedom which installs a tool in an end effector.

Fig. 4 is a schematic drawing of an operation panel of a teach pendant provided with some kind of changing switches.

Fig. 5 is a schematic drawing for explanations of homogeneous transformation matrixes which show relations of position and attitude between each coordinates for the workpiece handling robot and each coordinates for the tool handling robot.

Fig. 6 is a block diagram of a control means for manual teaching operations which relates to actuators of each robot.

Fig. 7 is a flow chart which explains controlling function at the initial phase.

Fig. 8 is a flow chart which explains the motion of "co-acting".

Fig. 9 is a flow chart which explains the "mode of co-acting cartesian coordinates manual operation" continued from B of Fig. 8.

Fig. 10 is a flow chart which explains the "mode of co-acting cartesian coordinates manual operation" continued from D of Fig. 9.

Fig. 11 consists of (a) to (c) which are schematic drawings for explanations of the teaching path under the motion of "co-action" when a teaching point A is moved.

Fig. 12 is a timing chart of each process till all of keys are released.

Fig. 13 is a schematic drawings for explanations under the motion of "co-action of position and attitude" of the workpiece handling robot and the tool handling robot, where (a) shows a state at the first positioning, (b) shows a state at the positioning after the tool was subjected to a movement of the workpiece, and (c) shows a state that a next point is being taught.

Fig. 14 is a flow chart which explains the "mode of co-acting each axis manual operation" continued from F of Fig. 8.

Fig. 15 is a flow chart which explains the "mode of co-acting each axis manual operation" continued from G of Fig. 14.

Fig. 16 is a flow chart which explains the "mode of co-acting each axis manual operation" continued from H of Fig. 15.

Fig. 17 is a flow chart which explains the "mode of sole-acting each axis manual operation" continued from J of Fig. 7.

Fig. 18 is a flow chart which explains the "mode of sole-acting each axis manual operation" continued from K of Fig. 17.

Fig. 19 is a flow chart which explains the "mode of sole-acting each axis manual operation" continued from L of Fig. 17.

Fig. 20 is a flow chart which explains the "mode of sole-acting cartesian coordinates manual operation" continued from M of Fig. 7.

Fig. 21 is a flow chart which explains the "mode of sole-acting cartesian coordinates manual operation" continued from N of Fig. 20.

Fig. 22 is a flow chart which explains the "mode of sole-acting cartesian coordinates manual operation" continued from O of Fig. 20.

Fig. 23 is a flow chart which explains the "mode of sole-acting cartesian coordinates manual operation" continued from P of Fig. 22.

Fig. 24 is schematic drawings for explanations of the co-operation in the prior art which does not associate workpiece handling robot with tool handling robot, i.e., of "sole-action", where (a) shows a state at the first positioning, (b) shows a state that tool is retired from workpiece, (c) shows a state that workpiece is being moved to a next teaching point, and (d) shows a state that tool is taught a next point on workpiece.

BEST MODE FOR PRACTICING THE INVENTION

A teaching control device for manual operation in an industrial robots-system of the present invention is disclosed as follows, by applying it to an embodiment of the welding robots-system which composed of a workpiece handling robot and a tool handling robot.

This robots-system is provided with a workpiece handling robot 1 which is capable to change "position and attitude" of a workpiece 1m as shown in Fig. 2 and a tool handling robot 2 which is capable to change "position and attitude" of a tool 2n for processing the workpiece as shown in Fig. 3. Both workpiece handling robot 1 and tool handling robot 2 are disposed to be faced each other as shown in Fig. 1, and position and attitude of workpiece 1m and position and attitude of tool 2n required in real processing operations, e.g., in the welding operations, can be manually taught before the real processing operations.

The workpiece handling robot 1 which moves a workpiece 1m held in an end effector 1A such as a robot hand is a manipulator of 6 degrees of freedom which has "joint variables" ϕ_1 to ϕ_6 corresponding to, for example, 6 joints 1a to 1f respectively. Similarly, the tool handling robot 2 which moves a tool 2n installed in an end effector 2A is also a manipulator of 6 degrees of freedom which has "joint variables" θ_1 to θ_6 corresponding to 6 joints 2a to 2f respectively. Each of joints 1a, 2a etc. indicated by diamond marks means a swivel-joints which rotates each of links $16W_1$, $16T_1$ to the direction of an arrow 1S, and each of joints 1b, 2b etc. indicated by double-circles means a bend-joint which bends each of links $16W_2$, $16T_2$ to

the direction of an arrow 1B. When some of joints are actuated at the same time, the workpiece and the tool can be moved to desired directions respectively, i.e., being moved to the direction of, for instance, X-axis only and being rotated around Y-axis only.

A teach pendant 3 and a control equipment 4 are provided in order to operate workpiece handling robot 1 and tool handling robot 2. Fig. 4 shows an operation panel of the teach pendant 3, on which an indicating device 5 and a stopping switch 6 are disposed. There is a robot changing switch 7 on the right hand side of the middle stage of the operation panel for selecting a robot which should be subjected to teaching operations, e.g., tilting it up means preparation of movement of workpiece handling robot 1 and tilting it down means preparation of movement of tool handling robot 2.

In the center of an operation panel of the teach pendant is provided a mode changing switch 8 in order to select "mode of each axis manual operation" or "mode of cartesian coordinates manual operation". An operation changing switch 9 is prepared on the left end of the operation panel, which is changed to select "sole-action" of each robot at teach working or "co-action" of both robots at teach working. This switch organizes "a selecting means for sole-action/co-action", which facilitates "manual operations of changing position and attitude of workpiece 1m on workpiece handling robot 1" and "manual operations of changing position and attitude of tool 2n on tool handling robot 2" separately, or facilitates "the manual operation of changing position and attitude of tool 2n on a tool handling robot 2" by means of associating with changing position and attitude of the workpiece 1m on a workpiece handling robot 1 so that position and attitude of the tool 2n against workpiece 1m can be always kept constant.

Therefore, the above-mentioned "co-action" of both robots at teaching operations means "the manual operation of changing position and attitude of tool 2n on a tool handling robot 2 so that position and attitude of the tool 2n against workpiece 1m are never changed while position and attitude of the workpiece 1m on a workpiece handling robot 1 are being changed" or "the manual operation of changing position and attitude of workpiece 1m on a workpiece handling robot 1 so that position and attitude of the workpiece 1m against tool 2n are never changed while position and attitude of the tool 2n on a tool handling robot 2 are being changed". But the former only is applied to an embodiment in the following description.

The portion of a scale in the center of the panel is a rate changing switch 10 which is used in order to select a desired rate for the movement of a workpiece 1m during the teach working so as to move it more slowly than a preset maximum value of a velocity table.

When a scale of, for example, 0.5 is selected, workpiece 1m can be moved at a half speed to the position which is taught by an operator. If the workpiece is required to move quickly, the scale of 1.0 is selected by an operator. Any rate may be selected during teaching operations. When the path from a present teaching point to a next one is rather long, the rate of, e.g., 1.0, is used till 80 % of said path and the rate of 0.1 is used during 20 % left thereof. As a result, workpiece 1m is quickly moved till the vicinity of the target, and it is slowly moved close by said target, by which it will be able to be accurately stopped at the target in a short time. Overshooting the target owing to selecting a higher rate, an operator has only to command returning to the target. It is convenient for a lower rate to relieve the tension of a teaching operator who tries to just stop the workpiece at the next teaching position. Therefore, the rates of this embodiment are provided with 4 of, e.g., 0.1, 0.2, 0.5, 1.0.

In the lower stage at the left hand side of the panel is provided an editing device 11 for teaching data. A group of keys 12 is disposed at the right hand side of the editing device. Each of keys 12a ~ 12f, 12A ~ 12F generates an output signal of "1", when it is pressed, and generates a signal of "0" when released. This group of keys 12 which consists of 12 push-buttons organizes a teaching key means which generates "actuating signals" for teaching operations.

Such a group of keys 12 is explained as follows; In the state that the mode changing switch 8 has been selected to "mode of each axis manual operation", when the keys 12a ~ 12f at the left column are pressed, each of joints of workpiece handling robot 1 rotates respectively, and when the keys 12A ~ 12F at the right column pressed, each of them reversely rotates respectively.

On the other hand, in the state that the mode changing switch 8 has been slected to "mode of cartesian coordinates manual operation", when the keys of the upper three are pressed, movements to the directions of X-axis, Y-axis, Z-axis of the world coordinates system 51 respectively as shown in Fig. 5 are performed, i.e., pressing the left keys 12a ~ 12c realizes movement to the positive directions of each axis, and pressing the right ones 12A ~ 12C realizes movement to the negative directions thereof. When the keys of the lower three are pressed, rotations to the directions of Euler's angles α, β, γ of the world coordinates system 51 respectively as shown in Fig. 5 are performed, i.e., pressing the left keys 12d ~ 12f realizes rotation to the positive directions, and pressing the right ones 12D ~ 12F realizes reverse rotation.

Such a teaching control device for manual operation in an industrial robots-system consists of a control equipment 4 which is provided with a computer 4A as a "control means for manual teaching operations",

5

which carries out a control by means of receiving commands of "actuating signals" from group of keys 12 and commands of "co-acting signal" from the operation changing switch 9 as shown in Fig. 1. This "control means for manual teaching operations" 4A provides, as shown in Fig. 6, a micro-processing unit 14 which consists of CPU, ROM and RAM etc. and surbo-drivers 15 which transform output signals of the micro-processing unit into actuating signals for actuators explained as follows.

As workpiece handling robot 1 and tool handling robot 2 are manipulators of 6 degrees of freedom respectively, the surbo-drivers 15 consist of 12 ones of $15W_1 - 15W_6$ and $15T_1 - 15T_6$ and actuators 17 as electric motors consist of actuators $17W_1 - 17W_6$ and $17T_1 - 17T_6$ corresponding to each of surbo-drivers 15 so that they can rotate the links $16W_1 - 16W_4$ and $16T_1 - 16T_4$ connected with the joints of robot 1 and 2.

The symbol 18W in Fig. 6 is a control cable which connects each of surbo-drivers 15W with the corresponding actuator 17W of workpiece handling robot 1, and the symbol 18T is also a control cable which connects each of surbo-drivers 15T with the corresponding actuator 17T of tool handling robot 2. The numeral 19 is an interface which transmits signals of "actuating value for each actuator", i.e., the symbol 19a indicates an interface for outputting, and 19b indicates a buffer. They have 12 windows corresponding to "joint variables" ϕ_1, ϕ_2, $\cdot$ $\cdot$ $\cdot$, ϕ_6 of workpiece handling robot 1 and corresponding to "joint variables" θ_1, θ_2, $\cdot$ $\cdot$ $\cdot$, θ_6 of tool handling robot 2 respectively.

This "control means for manual teaching operations" 4A includes a control program which carries out five processes described as follows;

The first process is to calculate actuating velocities of workpiece handling robot 1 under the rate "r" selected on the rate changing switch 10 when the commands of "actuating signals" from group of keys 12 and the commands of a "co-acting signal" from the operation changing switch 9 have been received. And this process includes to compute position and attitude of workpiece handling robot 1 at the starting time of manual teaching operations, and to compute position and attitude of tool 2n against workpiece 1m at the starting time of manual teaching operations.

The second process is to command carrying out the following third process by means of estimating the state after a preset infinitesimal time ΔT, e.g., one-twentieth of a second when "actuating signals" in the first process are maintained. Or this process is to command returning to the first process when "actuating signals" have already changed into different ones. Or this process is to command terminating teaching operations when all of "actuating signals" have already vanished.

The third process is not only to calculate position and attitude of workpiece handling robot 1 but to previously calculate position and attitude of tool handling robot 2 by use of position and attitude of tool 2n against workpiece 1m at the starting time of manual teaching operations, which were calculated at the first process, and by use of position and attitude of workpiece handling robot 1 at the starting time of manual teaching operations, which were calculated at the first process.

The fourth process is not only to calculate "joint variables" of workpiece handling robot 1 by use of position and attitude of workpiece handling robot 1 which have were calculated at the third process but to calculate "joint variables" of tool handling robot 2 by use of position and attitude of tool handling robot 2 which were calculated at the third process.

The fifth process is not only to previously calculate "actuating values for actuators" $a_{w1\text{-}i}$, $a_{w2\text{-}i}$, $\cdot$ $\cdot$ $\cdot$, $a_{w6\text{-}i}$ of workpiece handling robot 1 by use of "joint variables" of workpiece handling robot 1 which were calculated at the fourth process but to previously calculate "actuating values for actuators" $a_{t1\text{-}i}$, $a_{t2\text{-}i}$, $\cdot$ $\cdot$ $\cdot$, $a_{t6\text{-}i}$ of tool handling robot 2 by use of "joint variables" of tool handling robot 2. And this process includes not only to synchronously output the signals of "actuating values for actuators" $a_{w2\text{-}i}$, $a_{w2\text{-}i}$, $\cdot$ $\cdot$ $\cdot$, $a_{w6\text{-}i}$ of workpiece handling robot 1 and the signals of "actuating values for actuators" $a_{t1\text{-}i}$, $a_{t2\text{-}i}$, $\cdot$ $\cdot$ $\cdot$, $a_{t6\text{-}i}$ of tool handling robot 2 just after an infinitesimal time ΔT, e.g., one-twentieth of a second, but to command repeating on and after the second process.

The "control means for manual teaching operations" 4A provides a program for carrying out the above-mentioned "co-action" which associates the change of position and attitude of workpiece 1m on workpiece handling robot 1 with the change of position and attitude of tool 2n on tool handling robot 2. In addition to this program, the control means 4A also provides a program carrying out the "sole-action" which acts either workpiece handling robot 1 or tool handling robot 2 according to the robot changing switch 7 when "sole-action" which does not associate the change of position and attitude of workpiece 1m on workpiece handling robot 1 with the change of position and attitude of tool 2n on tool handling robot 2 is selected by the operation changing switch 9.

Referring to some of flow charts in and after Fig.7, the manual teaching operations of workpiece handling robot 1 and tool handling robot 2 in the above-mentioned system related to the present invention are described as follows:

6

[1] The "co-acting cartesian coordinates manual operation" is explained below, which is in a state that "mode of cartesian coordinates manual operation" is selected by the mode changing switch 8 and "co-action" is selected by the operation changing switch 9. This means the referential point 56 of workpiece 1m with respect to the world coordinates system 51 as shown in Fig. 5 is changed into desired position and attitude thereof without changing the relative position and attitude between tool 2n and workpiece 1m.

An operator chooses "co-action" in the operation changing switch 9, "mode of cartesian coordinates manual operation" in the mode changing switch 8 and "workpiece handling robot" in the robot changing switch 7 on the teach pendant 3. Moreover, a desired rate "r", e.g., 0.2, which is indicated as " r_b ", is chosen in the rate changing switch 10.

An operator presses desired keys, e.g., 12b, 12c and 12E. The procedure till they will be released is as follows;

[a] : The first process consists of the after-mentioned [a-1] to [a-4].

Actuating signals are inputted to the control equipment by means of pressing keys 12b, 12c and 12E [see step 1 in the flow chart of Fig. 7, such as ST1 is indicated after this.]. As the operation changing switch 9 is "on", i.e., being selected "co-action" [ST2], the robot changing switch 7 is "on", i.e., being designated "workpiece handling robot" [ST3] and the mode changing switch 8 is "on", i.e., being selected "mode of cartesian coordinates manual operation" [ST6 in Fig.8], the procedure is led to step 7. If the robot changing switch 7 is "off", i.e., being designated "tool handling robot" [ST3], the procedure for controlling later becomes impossible. In this case it is indicated on the indicating device that the robot changing switch 7 should be "on", i.e., a message of designating "workpiece handling robot" appears in an undrawn CRT etc. [ST4], the procedure is terminated at this time [ST5].

A workpiece handling robot 1 may be used a manipulator of 6 degrees of freedom or a positioner of less than 3 degrees of freedom. A manipulator of 6 degrees of freedom only is, however, applied to the control in this embodiment of the present invention, therefore, in step 7 it is discriminated whether workpiece handling robot 1 is a manipulator of 6 degrees of freedom or not.

As the degree of freedom of workpiece handling robot 1 is previously stored in "control means for manual teaching operations" 4A, the discrimination of whether workpiece handling robot 1 is 6 degrees of freedom is carried out by means of said stored signal. If workpiece handling robot 1 is a positioner, a message that the procedure for controlling later is impossible is indicated in an undrawn CRT etc. [ST8], the procedure is terminated at that time [ST9].

The program includes a protective program to prevent a reckless operation of the computer, so that "cartesian coordinates manual operation" may become impossible unless workpiece handling robot 1 is 6 degrees of freedom. As a positioner is generally less than 3 degrees of freedom, "cartesian coordinates manual operation" can not be carried out, but said positioner is capable to be carried out by means of "mode of each axis manual operation" only mentioned later. If the workpiece handling robot 1 is 6 degrees of freedom [ST7], the procedure is led to step 10.

[a-1]; Velocities for translation and rotation of the referential point 56 of workpiece 1m in the absolute coordinates system 51 are calculated as follows;

The velocities Vx_w, Vy_w, Vz_w, $V\alpha_w$, $V\beta_w$, $V\gamma_w$ are computed by use of actuating signals Sx, Sy, Sz, $S\alpha$, $S\beta$, $S\gamma$ generated by keys 12b, 12c and 12E, a designated rate "r_b" and maximum values Vx_{w0}, Vy_{w0}, Vz_{w0}, $V\alpha_{w0}$, $V\beta_{w0}$, $V\gamma_{w0}$ memorized in a velocity table for "cartesian coordinates manual operation" of workpiece 1m [ST10], from equations (1).

$$Vx_w = Sx \times r_b \times Vx_{w0}$$
$$Vy_w = Sy \times r_b \times Vy_{w0}$$
$$Vz_w = Sz \times r_b \times Vz_{w0}$$
$$V\alpha_w = S\alpha \times r_b \times V\alpha_{w0}$$
$$V\beta_w = S\beta \times r_b \times V\beta_{w0}$$
$$V\gamma_w = S\gamma \times r_b \times V\gamma_{w0} \qquad (1)$$

The above-mentioned Sx, Sy, · · · , $S\gamma$ are as follows;
pressing each of keys 12a ~ 12f produces a signal " + 1" for each output;
pressing each of keys 12A ~ 12F produces a signal "-1" for each output;
releasing each of keys 12a ~ 12f, 12A ~ 12F produces a signal "0" for each output.
Since keys 12b, 12c and 12E only are pressed in this example,

$Sx = 0$, thus, $Vx_w = 0$

$Sy = +1$, thus, $Vy_w = r_b \times Vy_{w0}$

$Sz = +1$, thus, $Vz_w = r_b \times Vz_{w0}$

$S\alpha = 0$, thus, $V\alpha_w = 0$

$S\beta = -1$, thus, $V\beta_w = -r_b \times V\beta_{w0}$

$S\gamma = 0$, thus, $V\gamma_w = 0$

[a-2] ; Position and attitude of workpiece handling robot 1 at the starting time of manual teaching operations are calculated by use of actuating signals as follows;

"Joint variables" ϕ_{1-0}, ϕ_{2-0}, $\cdot$ $\cdot$ $\cdot$ $\cdot$, ϕ_{6-0} of workpiece handling robot 1 at the starting time of manual teaching operations are inputted [ST11]. Position and attitude W_{2-0} of the holding point 53 of workpiece 1m with respect to the base point 52 of workpiece handling robot 1 is formulated as equation (3), by a product of homogeneous transformation matrixes of equation (2) which uses "link parameters" indicated by Denavit-Hartenberg notation.

$$A_{jw} = Rot(Z, \phi_j) \cdot Trans(a_{jw}, 0, d_{jw}) \cdot Rot(X, \alpha_{jw}) \qquad (2)$$

$$W_{2-0} = A_{1w} \cdot A_{2w} \cdot A_{3w} \cdot A_{4w} \cdot A_{5w} \cdot A_{6w} \qquad (3)$$

The simbols in equation (2) are as follows;

ϕ_j is a variable of j-th joint of workpiece handling robot 1.

a_{jw} is a length of the j-th link of workpiece handling robot 1, which is a fixed value.

d_{jw} is a distance between the (j-1)-th link and the j-th one of workpiece handling robot 1, which is a fixed value.

α_{jw} is an angle between the (j-1)-th link and the j-th one of workpiece handling robot 1, which is a fixed value.

[a-3] ; Position and the attitude of the tip point 57 of tool 2n with respect to the referential point 56 of workpiece 1m at the starting time of manual teaching operations are calculated.

"Joint variables" θ_{1-10}, θ_{2-0}, $\cdot$ $\cdot$ $\cdot$, θ_{6-0} of tool handling robot 2 at the starting time of manual teaching operations are inputted [ST12]. Position and attitude T_{2-0} of the installation point 55 of tool 2n with respect to the base point 54 of tool handling robot 2 is formulated as equation (5), by a product of homogeneous transformation matrixes of equation (4) which uses "link parameters" indicated by Denavit-Hartenberg notation.

$$A_{jt} = Rot(Z, \theta_j) \cdot Trans(a_{jt}, 0, d_{jt}) \cdot Rot(X, \alpha_{jt}) \qquad (4)$$

$$T_{2-0} = A_{1t} \cdot A_{2t} \cdot A_{3t} \cdot A_{4t} \cdot A_{5t} \cdot A_{6t} \qquad (5)$$

The simbols in equation (4) are as follows;

θ_j is a variable of the j-th joint of tool handling robot 2.

a_{jt} is a length of the j-th link of tool handling robot 2, which is a fixed value.

d_{jt} is a distance between the (j-1)-th link and the j-th one of tool handling robot 2, which is a fixed value.

α_{jt} is an angle between the (j-1)-th link and the j-th one of tool handling robot 2, which is a fixed value.

A homogeneous transformation matrix " world X_{w-0} " of position and attitude of the referential point 56 of the workpiece with respect to the world coordinates system 51 as shown in Fig. 5 is calculated by equation (6) [ST13].

$$world \ X_{w-0} = Z_w \cdot W_{2-0} \cdot E_w \qquad (6)$$

where Z_w is a homogeneous transformation matrix of position and attitude of the base point 52 of workpiece handling robot 1 with respect to the world coordinates system 51 of Fig. 5, and E_w is a homogeneous transformation matrix of position and attitude of the referential point 56 of the workpiece with respect to the holding point 53 of workpiece 1m. These data are previously stored in the "control means for manual teaching operations" 4A.

A homogeneous transformation matrix " world X_{t-0} " of position and attitude of the tip point 57 of

8

tool 2n with respect to the world coordinates system 51 is calculated by equation (7) [ST14].

$$\text{world } X_{t\text{-}o} = Z_t \cdot T_{2-o} \cdot E_t \qquad (7)$$

where Z_t is a homogeneous transformation matrix of position and attitude of the base point 54 of tool handling robot 2 with respect to the world coordinates system 51, and E_t is a homogeneous transformation matrix of position and attitude of the tip point 57 of the tool with respect to the installation point 55 of tool 2n. These data are also previously stored in the "control means for manual teaching operations" 4A.

Assuming that a homogeneous transformation matrix of position and attitude of the tip point 57 of tool 2n with respect to the referential point 56 of the workpiece is " wX_t ", a following equation is formulated.

$$\text{world } X_{t\text{-}o} = \text{world } X_{w\text{-}o} \cdot wX_t \qquad (8)$$

Therefore, wX_t is calculated by equation (9) [ST15 in Fig. 9].

$$wX_t = (\text{world } X_{w\text{-}o})^{-1} \cdot (\text{world } X_{t\text{-}o}) \qquad (9)$$

A homogeneous transformation matrix " world $X_{w\text{-}o}$ " of position and attitude of the referential point 56 of workpiece 1m with respect to the world coordinates system 51 is formulated as a following equation.

$$\text{world } X_{w-o} = \begin{bmatrix} n_x & o_x & a_x & p_x \\ n_y & o_y & a_y & p_y \\ n_z & o_z & a_z & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad \cdots\cdots (10)$$

By transforming the above equations, the data for position $X_{w\text{-}o}$, $Y_{w\text{-}o}$, $Z_{w\text{-}o}$ and the data of Euler's angles $\alpha_{w\text{-}o}$, $\beta_{w\text{-}o}$, $\gamma_{w\text{-}o}$ for attitude of the referential point 56 of the workpiece with respect to the world coordinates system 51 at the starting time of manual operations are obtained. The 6 equivalent parameters are calculated by means of following equations [ST16].

$$\text{world } X_{w-o} = \text{Trans}(X_{w-o}, Y_{w-o}, Z_{w-o}) \cdot \text{Rot}(Z, \alpha_{w-o})$$

$$\cdot \text{Rot}(Y, \beta_{w-o}) \cdot \text{Rot}(Z, \gamma_{w-o})$$

$$
= \begin{bmatrix}
\text{Cos}(\alpha_{w-o}) \text{Cos}(\beta_{w-o}) \text{Cos}(\gamma_{w-o}) - \text{Sin}(\alpha_{w-o}) \text{Sin}(\gamma_{w-o}) \\
\text{Sin}(\alpha_{w-o}) \text{Cos}(\beta_{w-o}) \text{Cos}(\gamma_{w-o}) + \text{Cos}(\alpha_{w-o}) \text{Sin}(\gamma_{w-o}) \\
-\text{Sin}(\beta_{w-o}) \text{Cos}(\gamma_{w-o}) \\
0
\end{bmatrix}
$$

$$
\begin{matrix}
-\text{Cos}(\alpha_{w-o}) \text{Cos}(\beta_{w-o}) \text{Sin}(\gamma_{w-o}) - \text{Sin}(\alpha_{w-o}) \text{Cos}(\gamma_{w-o}) \\
-\text{Sin}(\alpha_{w-o}) \text{Cos}(\beta_{w-o}) \text{Sin}(\gamma_{w-o}) - \text{Cos}(\alpha_{w-o}) \text{Cos}(\gamma_{w-o}) \\
\text{Sin}(\beta_{w-o}) \text{Cos}(\gamma_{w-o}) \\
0
\end{matrix}
$$

$$
\begin{matrix}
\text{Cos}(\alpha_{w-o}) \text{Sin}(\beta_{w-o}) & X_{w-o} \\
\text{Sin}(\alpha_{w-o}) \text{Sin}(\beta_{w-o}) & Y_{w-o} \\
\text{Cos}(\beta_{w-o}) & Z_{w-o} \\
0 & 1
\end{matrix}
$$

$$X_{w-o} = p_x, Y_{w-o} = p_y, Z_{w-o} = p_z \quad (11)$$

$$\alpha_{w-o} = \text{Cos}^{-1}(a_x / \text{Sin}(\beta_{w-o})) \quad (12)$$

$$\beta_{w-o} = \text{Cos}^{-1}(a_z) \quad (13)$$

$$\gamma_{w-o} = \text{Sin}^{-1}(o_z / \text{Sin}(\beta_{w-o})) \quad (14)$$

[a-4] ; Setting up i = 0, and a lapse of time Δt_{-1} from the starting time of manual operations is set equal to "0" [ST17].

[b] : The second process is as follows;

The discrimination of whether keys 12b, 12c and 12E previously pressed have been released or not, i.e., whether actuating signals are maintained or not, is carried out [ST18]. If all of actuating signals are maintained, a infinitesimal time ΔT is added to the lapse of time Δt_i [ST19, ST20], and carrying out the third process is commanded after the lapse of time is replaced with Δt_{i+1}. If all of keys 12b, 12c and 12E have already been released [ST21 in Fig. 9], the teaching operation is terminated [ST22]. If the keys have been pressed are different from previous ones, i.e., keys 12a, 12D and 12E have already been pressed instead of keys 12b, 12c and 12E [ST21], the procedure is repeated from step 1 of the first process by use of new actuating signals thereof.

[c] : The third process is as follows; This is carrying out by receiving the command from the second

process.

Position X_{w-i}, Y_{w-i}, Z_{w-i} and Euler's angle α_{w-i}, β_{w-i}, γ_{w-i} of attitude of the referential point 56 of workpiece 1m with respect to the world coordinates system 51 after the lapse of time Δ_{t-i}, i.e., after $\Delta T \times i$, are calculated [ST23 in Fig. 10].

$$X_{w-i} = X_{w-0} + Vx_w \cdot 1 \times \Delta t_i$$
$$Y_{w-i} = Y_{w-0} + Vy_w \times \Delta t_i$$
$$Z_{w-i} = Z_{w-0} + Vz_w \times \Delta t_i$$
$$\alpha_{w-i} = \alpha_{w-0} + V\alpha_w \times \Delta t_i$$
$$\beta_{w-i} = \beta_{w-0} + V\beta_w \times \Delta t_i$$
$$\gamma_{w-i} = \gamma_{w-0} + V\gamma_w \times \Delta t_i \qquad (15)$$

A homogeneous transformation matrix " world X_{w-i} " of position and attitude of the referential point 56 of workpiece 1m is calculated by equation (16) [ST24].

$$\text{world } X_{w-i} = \text{Trans}(X_{w-i}, Y_{w-i}, Z_{w-i}) \cdot \text{Rot}(Z, \alpha_{w-i}) \cdot \text{Rot}(Y, \beta_{w-i}) \cdot \text{Rot}(Z, \gamma_{w-i}) \qquad (16)$$

Even if workpiece 1m acts according to equation (16), position and attitude T_{2-i}, which relative position and attitude of tool 2n against workpiece 1m are never changed, of tool handling robot 2 are calculated.

A following equation is formulated as the above-mentioned equation (8).

$$\text{world } X_{t-i} = \text{world } X_{w-i} \cdot wX_t \qquad (17)$$

A following equation is formulated from the relation of coordinates as the above-mentioned equation (7).

$$\text{world } X_{t-i} = Z_t \cdot T_{2-i} \cdot E_t \qquad (18)$$

From equation (18), a following equation (19) is formulated.

$$T_{2-i} = (Z_t)^{-1} \cdot \text{world } X_{t-i} \cdot (E_t)^{-1} \qquad (19)$$

Substituting equation (17) into equation (19) results equation (20) [ST25].

$$T_{2-i} = (Z_t)^{-1} \cdot \text{world } X_{w-i} \cdot wX_t \cdot (E_t)^{-1} \qquad (20$$

On the other hand, equation (21) is formulated as an above-mentioned equation (6).

$$\text{world } X_{w-i} = Z_w \cdot W_{2-i} \cdot E_w \qquad (21)$$

and a homogeneous transformation matrix W_{2-i} of position and attitude of workpiece handling robot 1 can be calculated by equation (22) [ST26].

$$W_{2-i} = (Z_w)^{-1} \cdot \text{world } X_{w-i} \cdot (E_w)^{-1} \qquad (22)$$

[d] : The fourth process consists of the following [d-1] to [d-2].
[d-1] ; "Joint variables" θ_{1-i}, θ_{2-i}, $\cdot\cdot\cdot$, θ_{6-i} of tool handling robot 2 are obtained by inversely transforming T_{2-i} of equation (20) [ST27].
[d-2] : "Joint variables" ϕ_{1-i}, ϕ_{2-i}, $\cdot\cdot\cdot$, ϕ_{6-i} of workpiece handling robot 1 are obtained by inversely transforming W_{2-i} of equation (22) [ST28].
[e] : The fifth process is as follows;
Actuating quantities of "joint variables" per unit of "actuating values for actuators" of tool handling robot 2 and workpiece handling robot 1 respectively are assumed R_{t1}, R_{t2}, $\cdot\cdot\cdot$, R_{t6}, R_{w1}, R_{w2}, $\cdot\cdot\cdot$, R_{w6}, which are predetermined values every robot and are previously stored in the "control means for manual teaching operations" 4A.
Assuming that actuating values for actuators $17T_1$, $17T_2$, $\cdot\cdot\cdot$, $17T_6$ of tool handling robot 2

11

are a_{11-i} , a_{12-i} , $\cdot$ $\cdot$ $\cdot$, a_{16-i} and actuating values for actuators $17W_1$, $17W_2$, $\cdot$ $\cdot$ $\cdot$, $17W_6$ of workplece handling robot 1 are a_{w1-i} , a_{w2-i} , $\cdot$ $\cdot$ $\cdot$, a_{w6-i} they are as follows [ST29];

$a_{11-i} = \theta_{1-i} / R_{11}$

$a_{12-i} = \theta_{2-i} / R_{12}$

$a_{13-i} = \theta_{3-i} / R_{13}$

$a_{14-i} = \theta_{4-i} / R_{14}$

$a_{15-i} = \theta_{5-i} / R_{15}$

$a_{16-i} = \theta_{6-i} / R_{16}$ (101)

$a_{w1-i} = \phi_{1-i} / R_{w1}$

$a_{w2-i} = \phi_{2-i} / R_{w2}$

$a_{w3-i} = \phi_{3-i} / R_{w3}$

$a_{w4-i} = \phi_{4-i} / R_{w4}$

$a_{w5-i} = \phi_{5-i} / R_{w5}$

$a_{w6-i} = \phi_{6-i} / R_{w6}$ (102)

Such actuating values a_{11-i} , a_{12-i} , $\cdot$ $\cdot$ $\cdot$, a_{16-i} for actuators of tool handling robot 2 and actuating values a_{w1-i} , a_{w2-i} , $\cdot$ $\cdot$ $\cdot$, a_{w6-i} for actuators of workpiece handling robot 1 are outputted just after the lapse of time comes into $\Delta T \times i$ [ST30, ST31] , and the procedure is returned to step 18 of the second process.

The control function by means of the "control means for manual teaching operations" 4A, which includes an algorithm thereof, are described above. An example of actual teaching operations is explained referring to Fig. 11(a) as follows; In the case that position and attitude of a teaching point A_1 at the first postioning on workpiece 1m indicated by a solid line is moved to that of a teaching point A_2 at the second postioning thereon indicated by a single dotted line, an operator has only to press, e.g., once, a group of keys 12, if the path from the first teaching point A_1 till the next one A_2 is simple. In this operation, step 18 is repeated every after adding ΔT, e.g., one-twentieth of a second [ST19, ST20]. The workpiece 1m and tool 2n are moved according to the output signals of step 31 every said repetition.

The process is repeated till $\Delta T \times n$ every ΔT as shown in a timing chart of Fig. 12. The repetition from the second process till the fifth process every ΔT is comprehensible. The intervals of ΔT in Fig. 11(a) are indicated different each other, because workpiece 1m is not always moved same distance every ΔT and attitude of workpiece 1m is often changed three-dimensionally.

When the state which keys 12a, 12c and 12D are pressed is changed to the state which keys 12a and 12F are pressed, actuating signals are changed as a broken line indicated at the upper part of a timing chart in Fig. 12. Even if actuating signals are changed as above, the procedure is returned to step 1 from step 21, as long as all of signals are not "0". The procedure is carried out till step 31 according to actuating signals changed as above. In this case, actuators 17W, 17T actuate n times from the first $\Delta T \times 1$ till the last $\Delta T \times n$.

What all of actuating signals have changed to "0" at step 21 means unnecessity of moving workpiece 1m, and the controlling function is completed at a finishing point EE in the timing chart. After this, "co-action" is futhermore repeated or "sole-action" is carried out from step 2 as mentioned later.

The case that the above-mentioned "co-action" is repeated in spite that all of actuating signals have already changed to "0" means a case that position and attitude of tool 2n against workpiece 1m do not still become desired position and attitude thereof at the second positioning. In this case, the above-mentioned procedure is continued till the second positioning is completed. Such an example is bliefly described as follows;

If the path between point A_1 at the first positioning and point A_2 at the second positioning is straight and long, a rate changing swicth 10 is preferable to be changed as follows. The point a_1 and a_2 are chosen in the middle of the path between point A_1 and point A_2 as shown in Fig. 11(b). The rate of 1.0 is selected in the route from point A_1 till a_1, 0.5 from point a_1 till a_2, 0.1 from point a_2 till A_2. Each of points a_1, a_2, A_2 corresponds to the finishing point EE in Fig. 12 respectively. Position and attitude at a temporary point a_1 are ignored and are not memorized after arriving at a next temporary point of a_2. Similarly, position and attitude at the temporary point a_2 are also ignored. On the other hand, position and attitude at the point A_2 are memorized as teaching data.

Therefore, directly moving from point A_1 to A_2 is played back at the rate of 1.0 in real processing

operations of, for example, in the welding operations, so as to keep position and attitude of tool 2n against workpiece 1m at the starting time of manual operations. When the rate has been set up to a lower value in the final route from above-mentioned point a_2 till point A_2, it may be prevented from carelessly overshooting the target A_2 and it may be promoted to relieve the tension of a teaching operator.

5   In the case that there is a protrusion on the way from point A_1 to A_2 on workpiece 1m, the route for point A_2 should be avoided it. The route via points a_1 and a_2 which do not exist on the segment A_1 A_2 indicated by a broken line in Fig. 11(c) is selected for a teaching path. In this case, not only "mode of cartesian coordinates manual operation" may be adopted between point A_1 and a_1 but "mode of each axis manual operation" mentioned later may be adopted between point a_1, and a_2, moreover, "mode of cartesian

10   coordinates manual operation" may be adopted again between point a_2 and A_2. Each of points a_1, a_2, A_2 corresponds to the finishing point EE in Fig. 12. When "mode of each axis manual operation" is adopted between the point a_1 and a_2, it is also possible to change the rate at the point of a_{11} in the middle of the route between a_1 and a_2.

The state of the starting time of manual operations means the state of the first positioning as shown in

15   Fig. 13(a), therefore, the teaching point A is a point A_1. The state of the second positioning is achieved via points a_1, a_2 etc. by means of rotating workpiece 1m to the direction of the arrow 1p. The second positioning at the point A_2 is shown in Fig. 13(b). The "co-action" is carried out between Fig. 13(a) and Fig. 13(b). After the teaching point A is shifted to point A_2 at the second positioning, the next teaching point B and the point C after next shown in Fig. 13(c) may be taught by means of "sole-acting manual operation"

20   i.e., moving tool 2n under the condition that workpiece 1m is stopped, or moving workpiece 1m under the condition that tool 2n is stopped.

The above-mentioned description in Fig. 13 is comprehensible different from that of the prior art in Fig. 24. This means that tool 2n never leaves workpiece 1m between Fig. 13(a) and Fig. 13(b). tool 2n is subjected to the movement of workpiece 1m, and position and attitude of tool 2n against workpiece 1m are

25   always maintained.

[2] Next, "co-acting each axis manual operation" is explained below, which is in a state that "mode of each axis manual operation" is selected by the mode changing switch 8 and "co-action" is selected by the operation changing switch 9. This means that position and attitude of workpiece 1m are changed to desired ones thereof by means of joints of workpiece handling robot 1 without changing relative position

30   and attitude between tool 2n and workpiece 1m.

An operator chooses "co-action" in the operation changing switch 9, "mode of each axis manual operation" in the mode changing switch 8 and "workpiece handling robot" in the robot changing switch 7 on teach pendant 3. Moreover, a desired rate "r", e.g., 0.5, which is indicated as "r_c", is chosen in the rate changing switch 10.

35   An operator presses desired keys, e.g., 12b and 12D. The procedure till they will be released are as follows;

[a] : The first process consists of the after-mentioned [a-1] to [a-4].

Actuating signals are inputted into control equipment by means of pressing keys 12b and 12D [ST1 in Fig. 7]. As the operation changing switch 9 is "on", i.e., being selected "co-action" [ST2], the

40   robot changing switch 7 is "on", i.e., being designated "workpiece handling robot" [ST3 in Fig. 7] and the mode changing switch 8 is "off", i.e., being selected "mode of each axis manual operation" [ST6 in Fig.8], the procedure is led to step 32 in Fig. 14. If the robot changing switch 7 is "off", i.e., being designated "tool handling robot" [ST3], the procedure for controlling later becomes impossible. In this case it is indicated on the indicating device that the robot changing switch 7 should be

45   "on", i.e., a message of designating "workpiece handling robot" appears in an undrawn CRT etc. [ST4], the procedure is terminated at this time [ST5].

A workpiece handling robot 1 may be a manipulator of 6 degrees of freedom or a positioner of less than 3 degrees of freedom in this "mode of each axis manual operation". A manipulator of 6 degrees of freedom only is applied to controlling in the above-mentiond "mode of cartesian

50   coordinates manual operation". But a positioner of 3 degrees of freedom may be also applied to this embodiment, then, actuating signals generated by the group of keys 12 are S1 to S3 only.

[a-1]; Velocities for joints of workpiece handling robot 1 are calculated as follows;

The velocities $V1_w$, $V2_w$, $V3_w$, $V4_w$, $V5_w$, $V6_w$ are computed by use of actuating signals S1, S2, S3, S4, S5, S6 generated by keys 12b and 12D, a designated rate "r_c" and maximum values $V1_{w0}$

55   , $V2_{w0}$, $V3_{w0}$, $V4_{w0}$, $V5_{w0}$, $V6_{w0}$ memorized in a velocity table for "each axis manual operation" of workpiece handling robot 1 [ST32 n Fig. 14], from equations (23).

$$V1_w = S1 \times r_c \times V1_{w0}$$

13

$$V2_w = S2 \times r_c \times V2_{w0}$$
$$V3_w = S3 \times r_c \times V3_{w0}$$
$$V4_w = S4 \times r_c \times V4_{w0}$$
$$V5_w = S5 \times r_c \times V5_{w0}$$
$$V6_w = S6 \times r_c \times V6_{w0} \qquad (23)$$

The above-mentioned S1, S2, $\cdot$ $\cdot$ $\cdot$, S6 are as follows;
pressing each of keys 12a ~ 12f produces a signal " + 1 " respectively,
pressing each of keys 12A ~ 12F produces a signal "-1" respectively,
releasing each of keys 12a ~ 12f, 12A ~ 12F produces a signal "0" respectively.
Since keys 12b and 12D only are pressed in this example, similar to the above-mentiond example,

$$V1_w = 0, \ V3_w = 0, \ V5_w = 0, \ V6_w = 0.$$

[a-2] ; Position and attitude of workpiece handling robot 1 at the starting time of manual teaching operations are calculated by use of actuating signals as follows;

"Joint variables" ϕ_{1-0}, ϕ_{2-0}, $\cdot$ $\cdot$ $\cdot$ $\cdot$, ϕ_{6-0} of workpiece handling robot 1 at the starting time of manual teaching operations are inputted [ST33]. Position and attitude W_{2-0} of the holding point 53 of workpiece 1m with respect to the base point 52 of workpiece handling robot 1 is formulated as equation (3A), by a product of homogeneous transformation matrixes of equation (2A) which uses "link parameters" indicated by Denavit-Hartenberg notation.

$$A_{jw} = Rot(Z, \phi_j) \ ^* \ Trans(a_{jw}, 0, d_{jw}) \ ^* \ Rot(X, \alpha_{jw}) \qquad (2A)$$

$$W_{2-0} = A_{1w} \ ^* \ A_{2w} \ ^* \ A_{3w} \ ^* \ A_{4w} \ ^* \ A_{5w} \ ^* \ A_{6w} \qquad (3A)$$

Equations of (2A) and (3A) are just the same with above-mentioned equations (2) and (3) respectively. And ϕ_j, a_{jw}, d_{jw} and α_{jw} are also the same with the explanations after equations (2) and (3).

[a-3] ; Position and attitude of the tip point 57 of tool 2n with respect to the referential point 56 of workpiece 1m at the starting time of manual teaching operations are calculated as follows;

"Joint variables" θ_{1-0}, θ_{2-0}, $\cdot$ $\cdot$ $\cdot$, θ_{6-0} of tool handling robot 2 at the starting time of manual teaching operations are inputted [ST34]. Position and attitude T_{2-0} of the installation point 55 of tool 2n with respect to the base point 54 of tool handling robot 2 is formulated as equation (5A), by a product of homogeneous transformation matrixes of equation (4A) which uses "link parameters" indicated by Denavit-Hartenberg notation.

$$A_{jt} = Rot(Z, \theta_j) \ ^* \ Trans(a_{jt}, 0, d_{jt}) \ ^* \ Rot(X, \alpha_{jt}) \qquad (4A)$$

$$T_{2-0} = A_{1t} \ ^* \ A_{2t} \ ^* \ A_{3t} \ ^* \ A_{4t} \ ^* \ A_{5t} \ ^* \ A_{6t} \qquad (5A)$$

Equations of (4A) and (5A) are just the same with above-mentioned equations (4) and (5). And ϕ_j, a_{jt}, d_{jt} and α_{jt} are also the same with the explanations after equations (4) and (5).

A hmogeneous transformation matrix " world X_{w-0} " of position and attitude of the referential point 56 of the workpiece with respect to the world coordinates system 51 is calculated as a following equation [ST35].

$$\text{world } X_{w-0} = Z_w \ ^* \ W_{2-0} \ ^* \ E_w \qquad (6A)$$

This equation of (6A) is just the same with above-mentioned equations (6). Z_w and E_w are also the same with the explanations after equation (6).

A homogeneous transformation matrix " world X_{t-0} " of position and attitude of the tip point 57 of tool 2n with respect to the world coordinates system 51 is calculated as a following equation [ST36].

$$\text{world } X_{t-0} = Z_t \ ^* \ T_{2-0} \ ^* \ E_t \qquad (7A)$$

14

This equation of (7A) is just the same with above-mentioned equations (7). Z_i and E_i are also the same with the explanations after equation (7).

Assuming that a homogeneous transformation matrix of position and attitude of the tip point 57 of tool 2n with respect to the referential point 56 of the workpiece is " wX_i ", a following equation is formulated.

$$\text{world } X_{i\text{-}0} = \text{world } X_{w\text{-}0} \cdot wX_i \qquad (8A)$$

Therefore, wX_i is calculated by equation (9A) [ST37].

$$wX_i = (\text{world } X_{w\text{-}0})^{-1} \cdot (\text{world } X_{i\text{-}0}) \qquad (9A)$$

Equations of (8A) and (9A) are just the same with above-mentioned equations (8) and (9) respectively.

[a-4] ; Setting up i = 0, and a lapse of time Δt_i from the starting time of manual operations is set up equal to "0" [ST38].

[b] : The second process is as follows;

The discrimination of whether keys 12b and 12D previously pressed have been released or not, i.e., whether actuating signals are maintained or not, is carried out [ST39 in Fig. 15]. If all of actuating signals are maintained, a infinitesimal time of ΔT is added to the lapse of time Δt_i [ST40, ST41], and carrying out the third process is commanded after the lapse of time is replaced with Δt_{i+1}. If all of keys 12b and 12D have been already released [ST42], the teaching operation is terminated [ST43]. If keys have been pressed are different from previous ones, i.e., the key 12c has been already pressed instead of keys 12b and 12D [ST42], the procedure is repeated from step 1 of the first process by use of new actuating signals thereof.

[c] : The third process is as follows; This is carrying out by receiving the command from the second process. "Joint variables" $\phi_{1\text{-}i}$, $\phi_{2\text{-}i}$, $\cdots$, $\phi_{6\text{-}i}$ of workpiece handling robot 1 after the lapse of time Δt_i, i.e., after $\Delta T \times i$, are calculated [ST44 in Fig. 16].

$$\phi_{1\text{-}i} = \phi_{1\text{-}0} + V1_w \times \Delta t_i$$
$$\phi_{2\text{-}i} = \phi_{2\text{-}0} + V2_w \times \Delta t_i$$
$$\phi_{3\text{-}i} = \phi_{3\text{-}0} + V3_w \times \Delta t_i$$
$$\phi_{4\text{-}i} = \phi_{4\text{-}0} + V4_w \times \Delta t_i$$
$$\phi_{5\text{-}i} = \phi_{5\text{-}0} + V5_w \times \Delta t_i$$
$$\phi_{6\text{-}i} = \phi_{6\text{-}0} + V6_w \times \Delta t_i \qquad (24)$$

Position and attitude $W_{2\text{-}i}$ of the holding point 53 of workpiece 1m with respect to the base point 52 of workpiece handling robot 1 is formulated as equation (26), by a product of homogeneous transformation matrixes of equation (25) which uses "link parameters" indicated by Denavit-Hartenberg notation [ST45].

$$A_{jw} = \text{Rot}(z, \phi_{j\text{-}i}) \cdot \text{Trans}(a_{jw}, 0, d_{jw}) \cdot \text{Rot}(x, \alpha_{jw}) \qquad (25)$$

$$W_{2\text{-}i} = A_{1w} \cdot A_{2w} \cdot A_{3w} \cdot A_{4w} \cdot A_{5w} \cdot A_{6w} \qquad (26)$$

The simbols in equation (25) are as follows;

$\phi_{j\text{-}i}$ is a variable of j-th joint of workpiece handling robot 1.

a_{jw} is a length of the j-th link of workpiece handling robot 1, which is a fixed value.

d_{jw} is a distance between the (j-1)-th link and the j-th one of workpiece handling robot 1, which is a fixed value.

α_{jw} is an angle between the (j-1)-th link and the j-th one of workpiece handling robot 1, which is a fixed value.

When workpiece handling robot 1 acts according to equation (26), position and attitude of $T_{2\text{-}i}$, which relative position and attitude of tool 2n against workpiece 1m are never changed, of tool handling robot 2 are calculated. A homogeneous transformation matrix " world $X_{w\text{-}i}$ " of position and attitude of the referential point 56 of the workpiece with respect to the world coordinates system 51 is calculated by a following equation.

world $X_{w-i} = Z_w \cdot W_{2-i} \cdot E_w$ (27)

And a following equation is formulated as the above-mentioned equation (8).

world $X_{t-i} = $ world $X_{w-i} \cdot wX_i$ (28)

A following equation is formulated from relation of coordinates as above-mentioned equation (7).

world $X_{t-i} = Z_t \cdot T_{2-i} \cdot E_t$ (29)

From equation (29), a following equation (30) is formulated.

$T_{2-i} = (Z_t)^{-1} \cdot$ world $X_{t-i} \cdot (E_t)^{-1}$ (30)

Substituting equation (27) into equation (30) results equation (31), thus, T_{2-i} is calculated [ST46].

$T_{2-i} = (Z_t)^{-1} \cdot$ world $X_{w-i} \cdot wX_i \cdot (E_t)^{-1}$ (31)

[d] : The fourth process is as follows;

"Joint variables" θ_{1-i} , θ_{2-i} , $^* {}^* {}^*$, θ_{6-i} of tool handling robot 2 are obtained by inversely transforming T_{2-i} of equation (31) [ST47]. "Joint variables" ϕ_{1-i} , ϕ_{2-i} , $^* {}^* {}^*$, ϕ_{6-i} of workpiece handling robot 1 can be obtained by inversely transforming W_{2-i} of equation (26).

[e] : The fifth process is as follows;

Actuating quantities for joint variables per unit of actuating values for actuators of tool handling robot 2 and workpiece handling robot 1 respectively are assumed R_{t1} , R_{t2} , $^* {}^* {}^*$, R_{t6} , R_{w1} , R_{w2} , $^* {}^* {}^*$, R_{w6}. Actuating values for actuators of tool handling robot 2 are a_{t2-i} , a_{t2-i} , $^* {}^* {}^*$, a_{t6-i} are calculated from above-mentioned equation (101), and actuating values for actuators of workpiece handling robot 1 are a_{w1-i} , $a w_{2-i}$, $^* {}^* {}^*$, a_{w6-i} are calculated from equation (102) [ST48].

Such actuating values for actuators of tool handling robot 2 and actuating values for actuators of workpiece handling robot 1 are outputted just after the lapse of time comes into ΔT_{xi} [ST49, ST50], and the procedure is returned to step 39 of the second process.

The repetition of each process from generation of actuating signals till vanishment thereof is shown in a timing chart of Fig. 12 in the case of "mode of co-acting each axis manual operation". Fig. 11, Fig. 12 and Fig. 13 are also applied to this procedure.

In the state that workpiece 1m is moved to desired position and attitude by means of "mode of co-acting each axis manual operation" or "mode of co-acting cartesian coordinates manual operation", if "co-action" is selected by the operation changing switch 9 on teach pendant 3 and "tool handling robot" is designated by the robot changing switch 7, moving of new desired position and attitude, i.e., an operation from Fig. 13(b) to Fig. 13(c), are achieved by means of "mode of sole-acting each axis manual operation" of tool 2n or by means of "mode of sole-acting cartesian coordinates manual operation" with respect to the world coordinates system 51. These sole-action are described as follows.

The explanation below are "mode of sole-acting each axis manual operation" or "mode of sole-acting cartesian coordinates manual operation" which are the state of the art of the present invention. The present controlling system is comprehensible to be a compound system which is capable to carry out not only "the mode of sole-acting each axis or cartesian coordinates manual opertation" but "the mode of co-acting each axis or cartesian coordinates manual operation".

The "sole-acting each axis manual operation" is described below:

[1] The operation of changing position and attitude of tool 2n into desired position and attitude thereof by means of actuating joints of tool handling robot 2 is as follows;

An operator chooses "tool handling robot" in the robot changing switch 7, "mode of each axis manual operation" in the mode changing switch 8 and "sole-action" in the operation changing switch 9 on teach pendant 3. Moreover, a desired rate "r", e.g., 0.2, which is indicated as "r_b " is chosen in the rate changing switch 10. An operator presses desired keys, e.g., 12a and 12c. The procedure till they will be released are as follows;

[a] : The first process consists of following [a-1] to [a-3].

Actuating signals are inputted to control equipment by means of pressing keys 12a and 12c [ST1

16

In Fig. 7]. As the operation changing switch 9 is "off", i.e., being selected "sole-action" [ST2], the mode changing switch 8 is "off", i.e., being selected "mode of each axis manual operation" [ST51], and the robot changing switch 7 is "off", i.e., being designated "tool handling robot" [ST52 in Fig. 17], the procedure is led to step 53.

[a-1] ; Velocities for joints of tool handling robot 2 are calculated as follows:

The velocities $V1_i$, $V2_i$, $V3_i$, $V4_i$, $V5_i$, $V6_i$ are computed by use of actuating signals S1 , S2 , S3 , S4 , S5 , S6 generated by keys, a designated rate " r_b " and maximum values $V1_{10}$, $V2_{10}$, $V3_{10}$, $V4_{10}$, $V5_{10}$, $V6_{10}$ memorized in a velocity table for "each axis manual operation" of tool handling robot 2 [ST53], from equations (32).

$$V1_i = S1 \times r_b \times V1_{10}$$
$$V2_i = S2 \times r_b \times V2_{10}$$
$$V3_i = S3 \times r_b \times V3_{10}$$
$$V4_i = S4 \times r_b \times V4_{10}$$
$$V5_i = S5 \times r_b \times V5_{10}$$
$$V6_i = S6 \times r_b \times V6_{10} \qquad (32)$$

The above-mentioned S1, S2 , $\cdot$ $\cdot$ $\cdot$, S6 are as follows;
pressing each of keys 12a ~ 12f produces a signal " + 1" respectively,
pressing each of keys 12A ~ 12F produces a signal "-1" respectively,
releasing each of keys 12a ~ 12f, 12A ~ 12F produces a signal "0" respectively.
Since keys 12a and 12c only are pressed in this example, similar to the above-mentiond example,

$$V2_i = 0, V4_i = 0, V5_i = 0, V6_i = 0.$$

[a-2] ; "Joint variables" θ_{1-0}, θ_{2-0}, $\cdot$ $\cdot$ $\cdot$ $\cdot$, θ_{6-0} of tool handling robot 2 at the starting time of manual teaching operations are inputted [ST54].

[a-3] ; Setting up i.e., i = 0. and a lapse of time Δt_i from the starting time of manual operations is set up equal to "0" [ST55].

[b] : The second process is as follows;

The discrimination of whether keys 12a and 12c previously pressed have been released or not, i.e., whether actuating signals are maintained or not. is carried out [ST56 in Fig. 18]. If all of actuating signals are maintained, a infinitesimal time of ΔT is added to the lapse of time Δt_i [ST57, ST58], and carrying out the third process is commanded after the lapse of time is replaced with Δt_{i+1}. If all of keys 12a and 12c have been already released [ST59], the teaching operation is ternimated [ST60]. If keys have been pressed are different from previous ones, i.e., the keys 12a and 12D have been already pressed instead of keys 12a and 12c [ST59], the procedure is repeated from step 1 by use of new actuating signals thereof.

[c] : The third process is as follows; This is carrying out by receiving the command from the second process.

"Joint variables" θ_{1-i} , θ_{2-i} , $\cdot$ $\cdot$ $\cdot$, θ_{6-i} of tool handling robot 2 after the lapse of time Δt_i, i.e., after $\Delta T \times i$, are calculated [ST61].

$$\theta_{1-i} = \theta_{1-0} + V1_i \times \Delta t_i$$
$$\theta_{2-i} = \theta_{2-0} + V2_i \times \Delta t_i$$
$$\theta_{3-i} = \theta_{3-0} + V3_i \times \Delta t_i$$
$$\theta_{4-i} = \theta_{4-0} + V4_i \times \Delta t_i$$
$$\theta_{5-i} = \theta_{5-0} + V5_i \times \Delta t_i$$
$$\theta_{6-i} = \theta_{6-0} + V6_i \times \Delta t_i \qquad (33)$$

Such "joint variables" θ_{1-i} , θ_{2-i} , $\cdot$ $\cdot$ $\cdot$, θ_{6-i} of tool handling robot 2 are transformed into actuating values a_{i2-i} , $a_{i2 -i}$, $\cdot$ $\cdot$ $\cdot$ $\cdot$, a_{i6-i} for actuators thereof by use of following equations (101B) [ST62], which are outputted just after the lapse of time comes into Δt_i[ST63, ST64], and the procedure is returned to the second process.

$$a_{i1-i} = \theta_{1-i} / R_{i1}$$
$$a_{i2-i} = \theta_{2-i} / R_{i2}$$

17

$$a_{13-i} = \theta_{3-i} / R_{13}$$
$$a_{14-i} = \theta_{4-i} / R_{14}$$
$$a_{15-i} = \theta_{5-i} / R_{15}$$
$$a_{16-i} = \theta_{6-i} / R_{16} \qquad (101B)$$

This equation (101B) is the same with equation (101) mentioned above.

[2] The operation of changing position and attitude of workpiece 1m into desired position and attitude thereof by means of actuating joints of workpiece handling robot 1 is as follows. This procedure is the same with that of changing position and attitude of tool 2n into desired position and attitude thereof by means of actuating joints of tool handling robot 2, which has been described in section [1].

An operator chooses "workpiece handling robot" in the robot changing switch 7, "mode of each axis manual operation" in the mode changing switch 8 and "sole-action" in the operation changing switch 9 on teach pendant 3. Moreover, a desired rate "r", e.g., 0.5, which is indicated as "r_c" is chosen in the rate changing switch 10.

An operator presses desired keys, e.g., 12A and 12d. The procedure till they will be released are as follows:

[a] : The first process consists of following [a-1] to [a-3].

Actuating signals are picked up to control equipment by means of pressing keys 12A and 12d [ST1 in Fig. 7]. As the operation changing switch 9 is "off", i.e., being selected "sole-action" [ST2], the mode changing switch 8 is "off", i.e., being selected "mode of each axis manual operation" [ST51], and the robot changing switch 7 is "on", i.e., being designated "workpiece handling robot" [ST52 in Fig. 17], the procedure is led to step 65.

[a-1]: Velocities for joints of workpiece handling robot 1 are calculated as follows:

The velocities $V1_w$, $V2_w$, $V3_w$, $V4_w$, $V5_w$, $V6_w$ are computed by use of actuating signals S1, S2, S3, S4, S5, S6 generated by keys, a designated rate r_c" and maximum values $V1_{w0}$, $V2_{w0}$, $V3_{w0}$, $V4_{w0}$, $V5_{w0}$, $V6_{w0}$ memorized in a velocity table for "each axis manual operation" of workpiece handling robot 1 [ST65], from equation (23C) which is the same with the above-mentioned equation (23).

$$V1_w = S1 \times r_c \times V1_{w0}$$
$$V2_w = S2 \times r_c \times V2_{w0}$$
$$V3_w = S3 \times r_c \times V3_{w0}$$
$$V4_w = S4 \times r_c \times V4_{w0}$$
$$V5_w = S5 \times r_c \times V5_{w0}$$
$$V6_w = S6 \times r_c \times V6_{w0} \qquad (23C)$$

The above-mentioned S1, S2 , • • • , S6 are as follows;
pressing each of keys 12a ~ 12f produces a signal " + 1" respectively,
pressing each of keys 12A ~ 12F produces a signal "-1" respectively,
releasing each of keys 12a ~ 12f, 12A ~ 12F produces a signal "0" respectively.
Since keys 12A and 12d only are pressed in this example, similar to the above-mentiond example,

$$V2_w = 0, V3_w = 0, V5_w = 0, V6_w = 0.$$

[a-2] : "Joint variables" ϕ_{1-0}, ϕ_{2-0}, • • • • , ϕ_{6-0} of workpiece handling robot 1 at the starting time of manual teaching operations are inputted [ST66].

[a-3] : Setting up i = 0, and a lapse of time Δt_i from the starting time of manual operations is set up equal to "0" [ST67].

[b] : The second process is as follows;

The discrimination of whether keys 12A and 12d previously pressed have been released or not, i.e., whether actuating signals are maintained or not, is carried out [ST68 in Fig. 19]. If all of actuating signals are maintained, a infinitesimal time of ΔT is added to the lapse of time Δt_i [ST69, ST70], and carrying out the third process is commanded after the lapse of time is replaced with Δt_{i+1}. If all of keys 12A and 12d have been already released [ST71], the teaching operation is ternimated [ST72]. If keys have been pressed are different from previous ones, i.e., the keys 12a and 12d have been already pressed instead of keys 12A and 12d [ST71], the procedure is repeated from step 1 by use of new actuating signals thereof.

18

[c] : The third process is as follows; This is carrying out by receiving the command from the second process.

"Joint variables" ϕ_{1-i} , ϕ_{2-i} , $\cdots$, ϕ_{6-i} of workpiece handling robot 1 after the lapse of time Δt_i, i.e., after $\Delta T \times i$, are calculated [ST73].

$$\phi_{1-i} = \phi_{1-0} + V1_i \times \Delta t_i$$
$$\phi_{2-i} = \phi_{2-0} + V2_i \times \Delta t_i$$
$$\phi_{3-i} = \phi_{3-0} + V3_i \times \Delta t_i$$
$$\phi_{4-i} = \phi_{4-0} + V4_i \times \Delta t_i$$
$$\phi_{5-i} = \phi_{5-0} + V5_i \times \Delta t_i$$
$$\theta_{6-i} = \phi_{6-0} + V6_i \times \Delta t_i \qquad (33C)$$

This equation (33C) is the same with equation (33) mentioned above.

Such "joint variables" ϕ_{1-i} , ϕ_{2-i} , $\cdots$, ϕ_{6-i} of workpiece handling robot 1 are transformed into actuating values a_{w1-i} , a_{w2-i} , $\cdots$, a_{w6-i} for actuators thereof by use of following equations (102C) [ST74], which are outputted just after the lapse of time comes into Δt_i [ST75, ST76], and the procedure is returned to the second process.

$$a_{w1-i} = \phi_{1-i} / R_{w1}$$
$$a_{w2-i} = \phi_{2-i} / R_{w2}$$
$$a_{w3-i} = \phi_{3-i} / R_{w3}$$
$$a_{w4-i} = \phi_{4-i} / R_{w4}$$
$$a_{w5-i} = \phi_{5-i} / R_{w5}$$
$$a_{w6-i} = \phi_{6-i} / R_{w6} \qquad (102C)$$

This equation (102C) is the same with equation (102) mentioned above.

Next, "sole-acting cartesian coordinates manual operation" is described below:

[3] The operation of changing position and attitude of tool 2n into desired position and attitude thereof with respect to the world coordinates system 51 by means of actuating joints of tool handling robot 2 is as follows;

An operator chooses "tool handling robot" in the robot changing switch 7, "mode of cartesian coordinates manual operation" in the mode changing switch 8 and "sole-action" in the operation changing switch 9 on teach pendant 3. Moreover, a desired rate "r", e.g., 0.2, which is indicated as "r_b" is chosen in the rate changing switch 10.

An operator presses desired keys, e.g., 12b and 12c. The procedure till they will be released are as follows;

[a] : The first process consists of following [a-1] to [a-3].

Actuating signals are inputted to control equipment by means of pressing keys 12b and 12c [ST1 in Fig. 7]. As the operation changing switch 9 is "off", i.e., being selected "sole-action" [ST2], the mode changing switch 8 is "on", i.e., being selected "mode of cartesian coordinates manual operation" [ST51], and the robot changing switch 7 is "off", i.e., being designated "tool handling robot" [ST82 in Fig. 20], the procedure is led to step 83.

[a-1]; Velocities for translation and rotation of tool 2n in the world coordinates system 51 are calculated as follows;

The velocities Vx_i , Vy_i , Vz_i , $V\alpha_i$, $V\beta_i$, $V\gamma_i$ are computed by use of actuating signals Sx , Sy , Sz , $S\alpha$, $S\beta$, $S\gamma$ generated by the keys, a designated rate "r_b" and the maximum values Vx_{t0} , Vy_{t0} , Vz_{t0} , $V\alpha_{t0}$, $V\beta_{t0}$, $V\gamma_{t0}$ memorized in a velocity table for "cartesian coordinates manual operation" of tool 2n [ST83], from equations (35).

$$Vx_i = Sx \times r_b \times Vx_{t0}$$
$$Vy_i = Sy \times r_b \times Vy_{t0}$$
$$Vz_i = Sz \times r_b \times Vz_{t0}$$
$$V\alpha_i = S\alpha \times r_b \times V\alpha_{t0}$$
$$V\beta_i = S\beta \times r_b \times V\beta_{t0}$$
$$V\gamma_i = S\gamma \times r_b \times V\gamma_{t0} \qquad (35)$$

The above-mentioned Sx, Sy , $\cdots$, $S\gamma$ are as follows;
pressing each of keys 12a ~ 12f produces a signal " + 1" for each output;

pressing each of keys 12A ~ 12F produces a signal "-1" for each output;

releasing each of keys 12a ~ 12f, 12A ~ 12F produces a signal "0" for each output.

Since the key 12b and 12c only are pressed in this example, similar to the above-mentioned example,

$$Vx_i = 0, \; V\alpha_i = 0, \; V\beta_i = 0, \; V\gamma_i = 0.$$

[a-2] ; "Joint variables" $\theta_{1-0}, \theta_{2-0}, \cdot \cdot \cdot \cdot, \theta_{6-0}$ of tool handling robot 2 at the starting time of manual teaching operations are inputted [ST84]. And a homogeneous transformation matrix " world X_{t-0} " of position and attitude of the tip point 57 of tool 2n with respect to the world coordinates system 51 is calculated as a following equation [ST85].

$$\text{world } X_{t-0} = Z_1 \cdot T_{2-0} \cdot E_t \qquad (36)$$

Equation (36) is formulated as a following equation.

$$
\text{world } X_{t-o} =
\begin{bmatrix}
n_x & o_x & a_x & p_x \\
n_y & o_y & a_y & p_y \\
n_z & o_z & a_z & p_z \\
0 & 0 & 0 & 1
\end{bmatrix}
\qquad \cdots\cdots (37)
$$

By transforming the above equations, the data for position X_{t-0}, Y_{t-0}, Z_{t-0} and the data of Euler's angles α_{t-0}, β_{t-0}, γ_{t-0} for attitude of the tip point 57 of tool 2n with respect to the world coordinates system 51 at the starting time of manual operations are obtained. The 6 equivalent parameters are calculated by following equations .

$$\text{world } X_{t-0} = Trans(X_{t-0}, Y_{t-0}, Z_{t-0}) \cdot Rot(Z, \alpha_{t-0})$$
$$\cdot Rot(Y, \beta_{t-0}) \cdot Rot(Z, \tau_{t-0})$$

$$= \begin{bmatrix} Cos(\alpha_{t-0}) \ Cos(\beta_{t-0}) \ Cos(\tau_{t-0}) \ -Sin(\alpha_{t-0}) \ Sin(\tau_{t-0}) \\ Sin(\alpha_{t-0}) \ Cos(\beta_{t-0}) \ Cos(\tau_{t-0}) \ +Cos(\alpha_{t-0}) \ Sin(\tau_{t-0}) \\ -Sin(\beta_{t-0}) \ Cos(\tau_{t-0}) \\ 0 \end{bmatrix}$$

$$-Cos(\alpha_{t-0}) \ Cos(\beta_{t-0}) \ Sin(\tau_{t-0}) \ -Sin(\alpha_{t-0}) \ Cos(\tau_{t-0})$$
$$-Sin(\alpha_{t-0}) \ Cos(\beta_{t-0}) \ Sin(\tau_{t-0}) \ -Cos(\alpha_{t-0}) \ Cos(\tau_{t-0})$$
$$Sin(\beta_{t-0}) \ Cos(\tau_{t-0})$$
$$0$$

$$\begin{bmatrix} Cos(\alpha_{t-0}) \ Sin(\beta_{t-0}) & X_{t-0} \\ Sin(\alpha_{t-0}) \ Sin(\beta_{t-0}) & Y_{t-0} \\ Cos(\beta_{t-0}) & Z_{t-0} \\ 0 & 1 \end{bmatrix}$$

$$X_{t-0} = p_x , Y_{t-0} = p_y , Z_{t-0} = p_z \quad (38)$$

$$\alpha_{t-0} = Cos^{-1}(a_x / Sin(\beta_{t-0})) \quad (39)$$

$$\beta_{t-0} = Cos^{-1}(a_z) \quad (40)$$

$$\tau_{t-0} = Sin^{-1}(o_z / Sin(\beta_{t-0})) \quad (41)$$

By use of these equations (38), (39), (40) and (41), position and attitude of tool 2n are calculated [ST86].

[a-3] ; Setting up i = 0, and a lapse of time Δt_i from the starting time of manual operations is set up equal to "0" [ST87].

[b] : The second process is as follows;

The discrimination of whether the keys 12b and 12c previously pressed have been released or not, i.e., whether the actuating signals are maintained or not, is carried out [ST88 in Fig. 21]. If all of actuating signals are maintained, a Infinitesimal time ΔT is added to the lapse of time Δt_i [ST89, ST90], and carrying out the third process is commanded after the lapse of time is replaced with Δt_{i+1}. If all of the keys 12b and 12c have been already released [ST91], the teaching operation is terminated [ST92]. If the keys have been pressed are different from previous ones, i.e., the keys 12C and 12F have been already pressed instead of the keys 12b and 12c [ST91], the procedure is

repeated from step 1 by use of new actuating signals thereof. [c] : The third process is as follows; This is carrying out by receiving the command from the second process.

Position X_{t-i} , Y_{t-i} , Z_{t-i} and Euler's angle α_{t-i} , β_{t-i} , γ_{t-i} of the attitude of the tip point 57 of tool 2n with respect to the world coordinates system 51 after the lapse of time Δt $-_i$, i.e., after $\Delta T \times i$, are calculated.

$$X_{t-i} = X_{t-0} + Vx_t \times \Delta t_i$$
$$Y_{t-i} = Y_{t-0} + Vy_t \times \Delta t_i$$
$$Z_{t-i} = Z_{t-0} + Vz_t \times \Delta t_i$$
$$\alpha_{t-i} = \alpha_{t-0} + V\alpha_t \times \Delta t_i$$
$$\beta_{t-i} = \beta_{t-0} + V\beta_t \times \Delta t_i$$
$$\gamma_{t-i} = \gamma_{t-0} + V\gamma_t \times \Delta t_i \qquad (42)$$

A homogeneous transformation matrix " world X_{t-i} " of position and attitude of the tip point 57 of tool is calculated as a following equation.

$$\text{world } X_{t-i} = \text{Trans}(X_{t-i} , Y_{t-i} , Z_{t-i}) \cdot \text{Rot}(Z, \alpha_{t-i}) \cdot \text{Rot}(Y, \beta_{t-i}) \cdot \text{Rot}(Z, \gamma_{t-i}) \qquad (43)$$

Since position and attitude T_{2-i} of tool handling robot 2 is expressed as a following equation (44) similar to above-mentioned equation (20), "joint variables" θ_{1-i} , θ_{2-i} , $\cdot$ $\cdot$ $\cdot$, θ_{6-i} of tool handling robot 2 are obtained [ST93].

$$T_{2-i} = (Z_t)^{-1} \cdot \text{world } X_{w-i} \cdot wX_t \cdot (E_t)^{-1} \qquad (44)$$

Such "joint variables" θ_{1-i} , θ_{2-i} , $\cdot$ $\cdot$ $\cdot$, θ_{6-i} of tool handling robot 2 are transformed into actuating values a_{t1-i} , a_{t2-i} , $\cdot$ $\cdot$ $\cdot$ $\cdot$, a_{t6-i} for actuators thereof by use of following equations (101D) [ST94], which are outputted just after the lapse of time comes into Δt_i [ST95, ST96], and the procedure is returned to the second process.

$$a_{t1-i} = \theta_{1-i} / R_{t1}$$
$$a_{t2-i} = \theta_{2-i} / R_{t2}$$
$$a_{t3-i} = \theta_{3-i} / R_{t3}$$
$$a_{t4-i} = \theta_{4-i} / R_{t4}$$
$$a_{t5-i} = \theta_{5-i} / R_{t5}$$
$$a_{t6-i} = \theta_{6-i} / R_{t6} \qquad (101D)$$

This equation (101D) is the same with equation (101) mentioned above.

[4] The operation of changing position and attitude of workpiece 1m into desired position and attitude thereof with respect to the world coordinates system 51 by means of actuating joints of workpiece handling robot 1 is as follows;

An operator chooses "workpiece handling robot" in the robot changing switch 7, "mode of cartesian coordinates manual operation" in the mode changing switch 8 and "sole-action" in the operation changing switch 9 on teach pendant 3. This means "sole-acting cartesian coordinates manual operation of workpiece handling robot". Moreover, a desired rate "r", e.g., 0.5, which is indicated as "r_c " is chosen in the rate changing switch 10.

An operator presses desired keys, e.g., 12a and 12c. The procedure till they will be released are as follows;

[a] : The first process consists of following [a-1] to [a-3].

Actuating signals are taken into control equipment by means of pressing keys 12a and 12c [ST1 in Fig. 7]. As the operation changing switch 9 is "off", i.e., being selected "sole-action" [ST2], the mode changing switch 8 is "on", i.e., being selected "mode of cartesian coordinates manual operation" [ST51], and the robot changing switch 7 is "on", i.e., being designated "workpiece .handling robot" [ST82 in Fig. 20], the procedure is led to step 100 in Fig. 20.

A workpiece handling robot 1 may be a manipulator of 6 degrees of freedom or a positioner of less than 3 degrees of freedom. A manipulator of 6 degrees of freedom only is, however, applied to the control in this embodiment of the present invention, therefore, in step 100 it is discriminated whether workpiece handling robot 1 is a manipulator of 6 degrees of freedom or not.

As the degree of freedom of workpiece handling robot 1 is previously stored in the "control

22

means for manual teaching operations" 4A, the discrimination of whether workpiece handling robot 1 is 6 degrees of freedom is carried out by means of said stored signal. If workpiece handling robot 1 is a positioner, a message that the procedure for controlling later is impossible is indicated in an undrawn CRT etc. [ST101], the procedure is terminated at that time [ST102]. If workpiece handling robot 1 is 6 degrees of freedom [ST100], the procedure is led to step 103.

[a-1]; Velocities for translation and rotation of workpiece 1m in the world coordinates system 51 are calculated as follows;

The velocities Vx_w, Vy_w, Vz_w, $V\alpha_w$, $V\beta_w$, $V\gamma_w$ are computed by use of actuating signals Sx, Sy, Sz, $S\alpha$, $S\beta$, $S\gamma$ generated by the keys, a designated rate "r_c" and the maximum values Vx_{w0}, Vy_{w0}, Vz_{w0}, $V\alpha_{w0}$, $V\beta_{w0}$, $V\gamma_{w0}$ memorized in a velocity table for "cartesian coordinates manual operation" of workpiece 1m [ST103], from equations (45).

$$Vx_w = Sx \times r_c \times Vx_{w0}$$
$$Vy_w = Sy \times r_c \times Vy_{w0}$$
$$Vz_w = Sz \times r_c \times Xz_{w0}$$
$$V\alpha_w = S\alpha \times r_c \times V\alpha_{w0}$$
$$V\beta_w = S\beta \times r_c \times V\beta_{w0}$$
$$V\gamma_w = S\gamma \times r_c \times V\gamma_{w0} \qquad (45)$$

The above-mentioned Sx, Sy, ••• , $S\gamma$ are as follows;
pressing each of keys 12a ~ 12f produces a signal "+1" for each output;
pressing each of keys 12A ~ 12F produces a signal "-1" for each output;
releasing each of keys 12a ~ 12f, 12A ~ 12F produces a signal "0" for each output.
Since the keys 12a and 12c only are pressed in this example, similar to the above-mentioned example,

$$Vy_w = 0, V\alpha_w = 0, V\beta_w = 0, V\gamma_w = 0.$$

[a-2] ; "Joint variables" ϕ_{1-0}, ϕ_{2-0}, ••••, ϕ_{6-0} of workpiece handling robot 1 at the starting time of manual teaching operations are inputted [ST104]. And a homogeneous transformation matrix " world X_{w-0} " of position and attitude of the referential point 56 of workpiece 1m with respect to the world coordinates system 51 is calculated as a following equation [ST105].

$$\text{world } X_{w-0} = Z_w \cdot T_{2-0} \cdot E_w \qquad (46)$$

Equation (46) is formulated as a following equation.

$$\text{world } X_{w-o} = \begin{bmatrix} n_x & o_x & a_x & p_x \\ n_y & o_y & a_y & p_y \\ n_z & o_z & a_z & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad \cdots\cdots (47)$$

By transforming the above equations, the data for position X_{w-o}, Y_{w-o}, Z_{w-o} and the data of Euler's angles α_{w-o}, β_{w-o}, γ_{w-o} for attitude of the tip referential point 56 of workpiece 1m with respect to the world coordinates system 51 at the starting time of manual operations are obtained. The 6 equivalent parameters are calculated by following equations .

$$\text{world } X_{w-o} = \text{Trans}(X_{w-o}, Y_{w-o}, Z_{w-o}) \cdot \text{Rot}(Z, \alpha_{w-o})$$

$$\cdot \text{Rot}(Y, \beta_{w-o}) \cdot \text{Rot}(Z, \gamma_{w-o})$$

$$
= \begin{bmatrix}
\cos(\alpha_{w-o})\cos(\beta_{w-o})\cos(\gamma_{w-o}) - \sin(\alpha_{w-o})\sin(\gamma_{w-o}) \\
\sin(\alpha_{w-o})\cos(\beta_{w-o})\cos(\gamma_{w-o}) + \cos(\alpha_{w-o})\sin(\gamma_{w-o}) \\
-\sin(\beta_{w-o})\cos(\gamma_{w-o}) \\
0
\end{bmatrix}
$$

$$
\begin{array}{l}
-\cos(\alpha_{w-o})\cos(\beta_{w-o})\sin(\gamma_{w-o}) - \sin(\alpha_{w-o})\cos(\gamma_{w-o}) \\
-\sin(\alpha_{w-o})\cos(\beta_{w-o})\sin(\gamma_{w-o}) - \cos(\alpha_{w-o})\cos(\gamma_{w-o}) \\
\sin(\beta_{w-o})\cos(\gamma_{w-o}) \\
0
\end{array}
$$

$$
\begin{array}{ll}
\cos(\alpha_{w-o})\sin(\beta_{w-o}) & X_{w-o} \\
\sin(\alpha_{w-o})\sin(\beta_{w-o}) & Y_{w-o} \\
\cos(\beta_{w-o}) & Z_{w-o} \\
0 & 1
\end{array}
$$

$$X_{w-o} = p_x, Y_{w-o} = p_y, Z_{w-o} = p_z \quad (48)$$

$$\alpha_{w-o} = \cos^{-1}(a_x / \sin(\beta_{w-o})) \quad (49)$$

$$\beta_{w-o} = \cos^{-1}(a_z) \quad (50)$$

$$\gamma_{w-o} = \sin^{-1}(o_z / \sin(\beta_{w-o})) \quad (51)$$

By use of these equations (48), (49), (50) and (51), position and attitude of workpiece 1m are calculated [ST106].

[a-3] ; Setting up i = 0, and a lapse of time Δt_i from the starting time of manual operations is set up equal to "0" [ST107].

[b] : The second process is as follows;

The discrimination of whether the keys 12a and 12c previously pressed have been released or not, i.e., whether the actuating signals are maintained or not, is carried out [ST108 in Fig. 23]. If all of actuating signals are maintained, a infinitesimal time ΔT is added to the lapse of time Δt_i [ST109, ST110], and carrying out the third process is commanded after the lapse of time is replaced with Δt_{i+1}. If all of the keys 12a and 12c have been already released [ST111], the teaching operation is

24

terminated [ST112]. If the keys have been pressed are different from previous ones. i.e., the keys 12a, 12c and 12E have been already pressed instead of the keys 12a and 12c [ST111], the procedure is repeated from step 1 by use of new actuating signals thereof.

[c] : The third process is as follows; This is carrying out by receiving the command from the second process.

Position X_{w-i}, Y_{w-i}, Z_{w-i} and Euler's angle α_{w-i}, β_{w-i}, γ_{w-i} of the attitude of the referential point 56 of workpiece 1m with respect to the world coordinates system 51 after the lapse of time Δt_{-i}, i.e., after $\Delta T \times i$, are calculated.

$$X_{w-i} = X_{w-o} + Vx_w \times \Delta t_i$$
$$Y_{w-i} = Y_{w-o} + Vy_w \times \Delta t_i$$
$$Z_{w-i} = Z_{w-o} + Vz_w \times \Delta t_i$$
$$\alpha_{w-i} = \alpha_{w-o} + V\alpha_w \times \Delta t_i$$
$$\beta_{w-i} = \beta_{w-o} + V\beta_w \times \Delta t_i$$
$$\gamma_{w-i} = \gamma_{w-o} + V\gamma_w \times \Delta t_i \qquad (52)$$

A homogeneous transformation matrix " world X_{i-i} " of position and attitude of the referential point 56 of workpiece is calculated as a following equation.

$$\text{world } X_{w-i} = \text{Trans}(X_{w-i}, Y_{w-i}, Z_{w-i}) \cdot \text{Rot}(Z, \alpha_{w-i}) \cdot \text{Rot}(Y, \beta_{w-i}) \cdot \text{Rot}(Z, \gamma_{w-i}) \qquad (53)$$

Since position and attitude W_{2-i} of workpiece handling robot 1 is expressed as a following equation (54) similar to above-mentioned equation (22), "joint variables" ϕ_{1-i}, ϕ_{2-i}, $\cdot$ $\cdot$ $\cdot$, ϕ_{6-i} of workpiece handling robot 1 are obtained [ST113].

$$W_{2-i} = (Z_w)^{-1} \cdot \text{world } X_{w-i} \cdot (E_w)^{-1} \qquad (54)$$

Such joint variables ϕ_{1-i}, ϕ_{2-i}, $\cdot$ $\cdot$ $\cdot$, ϕ_{6-i} of workpiece handling robot 1 are transformed into actuating values a_{w1-i}, a_{w2-i}, $\cdot$ $\cdot$ $\cdot$ $\cdot$, a_{w6-i} for actuators thereof by use of following equations (102E) [ST114], which are outputted just after the lapse of time comes into Δt_i [ST115, ST116], and the procedure is returned to the second process.

$$a_{w1-i} = \phi_{1-i} / R_{w1}$$
$$a_{w2-i} = \phi_{2-i} / R_{w2}$$
$$a_{w3-i} = \phi_{3-i} / R_{w3}$$
$$a_{w4-i} = \phi_{4-i} / R_{w4}$$
$$a_{w5-i} = \phi_{5-i} / R_{w5}$$
$$a_{w6-i} = \phi_{6-i} / R_{w6} \qquad (102E)$$

This equation (102E) is the same with equation (102) mentioned above.

In above-mentioned "co-acting cartesian coordinates manual operations", the world coordinates system is applied to the coordinates system in order to regulate movement of axial directions of each axis or rotation around each axis in the cartesian coordinates relating to position and attitude of workpiece handling robot 1. The coordinates system at the base point 52 of the workpiece handling robot 1 as shown in Fig. 5 may be applied to the coordinates system related to the present invention instead of the world coordinates system.

In such case, equations (6), (7), (8), (9) and (10) in the first process are replaced with following ones.

A homogeneous transformation matrix " $_{w1}X_{w-o}$ " of position and attitude of the referential point 56 of workpiece with respect to the base point 52 of workpiece handling robot 1 is as follows;

$$_{w1}X_{w-o} = W_{2-o} \cdot E_w \qquad (6X)$$

where a matrix W_{2-o} is given by equation (3), and E_w is a homogeneous transformation matrix of position and attitude of the referential point 56 of workpiece with respect to the holding point 53 of workpiece 1m. The data of this E_w is previously stored, as an example mentioned above, in the "control means for manual teaching operations" 4A.

A homogeneous transformation matrix " $_{T1}X_{t-o}$ " of position and attitude of the tip point 57 of tool 2n with respect to the base point 54 of tool handling robot 2 is as follows;

$$_{T1}X_{t-o} = T_{2-o} \cdot E_t \qquad (7X)$$

where a matrix T_{2-o} is given by equation (5), and E_t is a homogeneous transformation matrix of position and attitude of the tip point 57 of tool with respect to the installation point 55 of tool 2n. The data of this E_t is also previously stored, as an example mentioned above, in the "control means for manual teaching operations" 4A.

A following equation (8X) is formulated by use of a homogeneous transformation matrix Z_w of position and attitude of the base point 52 of workpiece handling robot 1 with respect to the world coordinates system as shown in Fig. 5, a homogeneous transformation matrix Z_t of position and attitude of the base point 54 of tool handling robot 2 with respect to the world coordinates system, and a homogeneous transformation matrix wX_t of position and attitude of the tip point 57 of tool 2n with respect to the referential point 56 of workpiece.

$$Z_t \cdot {}_{T1}X_{t-o} = Z_w \cdot {}_{w1}X_{w-o} \cdot wX_t \qquad (8X)$$

Therefore, wX_t is calculated from a following equation.

$$wX_t = ({}_{w1}X_{w-o})^{-1} \cdot Z_w^{-1} \cdot Z_t \cdot {}_{T1}X_{t-o} \qquad (9X)$$

A homogeneous transformation matrix ${}_{w1}X_{w-o}$ of position and attitude of the referential point 56 of workpiece with respect to the base point 52 of workpiece handling robot 1 is as follows;

$$
{}_{w1}X_{w-o} = \begin{bmatrix}
n_x & o_x & a_x & p_x \\
n_y & o_y & a_y & p_y \\
n_z & o_z & a_z & p_z \\
0 & 0 & 0 & 1
\end{bmatrix} \qquad \cdots\cdots (10X)
$$

And equations (16), (17), (18), (19), (20) (21) and (22) in the third process are replaced with following ones.

A homogeneous transformation matrix ${}_{w1}X_{w-i}$ of position and attitude of the referential point 56 of workpiece with respect to the base point 52 of workpiece handling robot 1 is calculated from equation (16X).

$$_{w1}X_{w-i} = \text{Trans}(X_{w-i}, Y_{w-i}, Z_{w-i}) \cdot \text{Rot}(Z, \alpha_{w-i}) \cdot \text{Rot}(Y, \beta_{w-i}) \cdot \text{Rot}(Z, \gamma_{w-i}) \qquad (16X)$$

Even if workpiece 1m acts according to equation (16X), position and attitude T_{2-i} , which relative position and attitude of tool 2n against workpiece 1m are never changed, of tool handling robot 2 can be calculated as follows.

A following equation (18X) is formulated as the above-mentioned equation (8X).

$$Z_t \cdot {}_{T1}X_{t-i} = Z_w \cdot {}_{w1}X_{w-i} \cdot wX_t \qquad (17X)$$

A following equation is formulated from the relation of coordinates as the above-mentioned equation (7X).

$$_{T1}X_{t-i} = T_{2-o} \cdot E_t \qquad (18X)$$

From equation (18X), a following equation (19X) is formulated.

26

$$T_{2\text{-i}} = {}_\text{Ti}X_{\text{i-i}}\,(E_\text{i}\,)^{-1} \qquad (19X)$$

Substituting equation (17X) into equation (19X) results equation (20X).

$$T_{2\text{-i}} = (Z_\text{i}\,)^{-1} \cdot Z_\text{w} \cdot {}_\text{wi}X_{\text{w-i}} \cdot wX_\text{i} \cdot (E_\text{i}\,)^{-1} \qquad (20X)$$

On the other hand, equation (21X) is formulated as an above-mentioned equation (6X).

$$_\text{wi}X_{\text{w-i}} = W_{2\text{-i}} \cdot E_\text{w} \qquad (21X)$$

and a homogeneous transformation matrix $W_{2\text{-i}}$ of position and attitude of workpiece handling robot 1 can be calculated by equation (22X).

$$W_{2\text{-i}} = {}_\text{wi}X_{\text{w-i}} \cdot (E_\text{w})^{-1} \qquad (22X)$$

In the teaching operations by use of "co-acting manual operation", as described above, "actuating values for actuators" of the workpiece handling robot and "actuating values for actuators" of the tool handling robot are computed by means of estimating a state after a previously fixed constant infinitesmal time. When the lapse of time comes into a predetermined time, "actuating values for actuators" of the tool handling robot and "actuating values for actuators" of the workpiece handling robot are synchronously outputted, therefore, the joints of the workpiece handling robot and joints of the tool handling robot are actuated according to the output signals respectively.

As the co-action which associates the workpiece with the tool while pressing the keys is synchronously achieved, the relative position and attitude of the tool against the workpiece is always constant, which is a specific effect of the present invention. In addition, the relative position and attitude of the tool against the workpiece is stopped maintaining previous ones after releasing the keys.

When the keys are released, the robots are really stopped after the above-mentiond infinitesimal time, but the movement of workpiece and tool are not influenced if a preferable rate is selected in the rate changing switch. And the workpiece and the tool are acculately stopped at a desired position by means of movement till the vicinity of a target In a high speed and movement close to said target in a lower speed.

The rapid and simplified teaching operations are established owing to unnecessity of retiring the tool from the workpiece in order to avoid interference of the tool with the workpiece. Even if position and attitude of the workpiece are changed, relative position and attitude of the tool against the workpiece are never changed. Therefore, it becomes easy to find position and attitude of the tool against the workpiece at the last teaching point, enabling a correct teaching at a next desired point.

Claims

1. A teaching control device for manual operation in an industrial robots-system, which is provided with a workpiece handling robot (1) that is capable to change position and attitude of a workpiece (1m) and a tool handling robot (2) that is capable to change position and attitude of a tool (2n) processing said workpiece (1m), comprising:

   a selecting means for sole-action/co-action (9) for enabling to select sole-acting manual operation that facilitates changing position and attitude of workpiece (1m) on said workpiece handling robot (1) and changing position and attitude of tool (2n) on said tool handling robot (2) separately, or to select co-acting manual operation that facilitates changing position and attitude of tool (2n) on said tool handling robot (2) co-acting with changing position and attitude of workpiece (1m) on said workpiece handling robot (1) so that position and attitude of the tool (2n) against workpiece (1m) can be always kept constant;

   a teaching key means (12) outputting actuating signals for changing position and attitude of said workpiece (1m);

   a control means for manual teaching operatoins (4A) carrying out control according to the after-mentioned process by means of receiving actuating signals from said teaching key means (12) and a co-acting signal from said selecting means for sole-action/co-action (9);

   said control means for manual teaching operatoins (4A) is a computer carries out control comprising following processes;

   the first process consists of taking actuating signals and computing position and attitude of workpiece handling robot (1) at the starting time of manual teaching operations and position and

attitude of tool (2n) against workpiece (1m) at the starting time of manual teaching operations;

the second process consists of commanding to carry out the following third process by means of estimating the state after a preset infinitesimal time (ΔT), when actuating signals in the first process are maintained, and commanding to return to the first process when actuating signals have already changed into different ones, and commanding to terminate teaching operations, when actuating signals have already vanished;

the third process consists of not only calculating position and attitude of workpiece handling robot (1) but previously calculating position and attitude of tool handling robot (2) by means of position and attitude of tool (2n) against workpiece (1m) at the starting time of manual teaching operations, which were calculated at the first process, and by means of position and attitude of workpiece handling robot (1) at the starting time of manual teaching operations, which were calculated at the first process;

the fourth process consists of only calculating joint variables of workpiece handling robot (1) by means of position and attitude of workpiece handling robot (1) which were calculated at the third process but calculating joint variables of tool handling robot (2) by means of position and attitude of tool handling robot (2) which were calculated at the third process;

The fifth process consist of not only previously calculating actuating values ($a_{w1\text{-}i}$, $a_{w2\text{-}i}$, $\cdot$ $\cdot$ $\cdot$, $a_{w6\text{-}i}$) for actuators of workpiece handling robot (1) 1 by means of joint variables (ϕ_1 , ϕ_2 , $\cdot$ $\cdot$ $\cdot$, ϕ_6) of workpiece handling robot (1) 1 which were calculated at the fourth process but to previously calculating actuating values ($a_{t1\text{-}i}$, $a_{t2\text{-}i}$, $\cdot$ $\cdot$ $\cdot$, $a_{t6\text{-}i}$) for actuators of tool handling robot (2) 2 by means of joint variables (θ_1 , θ_2 , $\cdot$ $\cdot$ $\cdot$, θ_6) of tool handling robot (2) which were calculated at the fourth process, in addition, including not only to output signals of actuating values ($a_{w2\text{-}i}$, $a_{w2\text{-}i}$, $\cdot$ $\cdot$ $\cdot$, $a_{w6\text{-}i}$) for actuators of workpiece handling robot (1) 1 and signals of actuating values ($a_{t1\text{-}i}$, $a_{t2\text{-}i}$, $\cdot$ $\cdot$ $\cdot$, $a_{t6\text{-}i}$) for actuators of tool handling robot (2) 2 at the same time just after an infinitesimal time (ΔT), but to command repeating on and after the second process.

2. A teaching control device for manual operations according to claim 1, wherein:
   said actuating signals of the teaching key means (12) may be adopted the signals commanding translation along each axis or rotation around each axis in the cartesian coordinates of position and attitude of workpiece handling robot (1).

3. A teaching control device for manual operations according to claim 1, wherein:
   said actuating signals of the teaching key means (12) may be adopted the signals commanding motions of joints (1a, 1b, 1c, 1d, 1e, 1f) of workpiece handling robot (1).

F I G. 1

F I G. 2

F I G. 3

F I G. 4

32

FIG. 5

FIG. 6

F I G. 7

F I G. 8

(A)

$$\downarrow$$

NO ← ST 6 — mode changing switch 8 on ?

(mode of each axis manual operation)

(F)

YES (mode of cartesian coordinates manual operation)

workpiece handling robot 6 degrees of freedom ? — ST 7 — NO → ST 8

error message is indicated

YES

ST 10 — velocities Vx_w Vy_w Vz_w $V\alpha_w$ $V\beta_w$ $V\gamma_w$ for cartesian coordinates manual operation of a workpiece are calculated by use of eq. (1).

END — ST 9

joint variables ϕ_{1-0} ϕ_{2-0} ϕ_{3-0} ϕ_{4-0} ϕ_{5-0} ϕ_{6-0} of workpiece handling robot at starting time of manual operation are inputted. — ST 11

joint variables θ_{1-0} θ_{2-0} θ_{3-0} θ_{4-0} θ_{5-0} θ_{6-0} of workpiece handling robot at starting time of manual operation are inputted. — ST 12

homogeneous transformation matrix "world X_{w-0}" of position and attitude of workpiece with respect to world coordinates system at starting time of manual operations is calculated from eq. (6). — ST 13

homogeneous transformation matrix "world X_{w-0}" of position and attitude of tool with respect to world coordinates system at starting time of manual operations is calculated from eq. (7). — ST 14

(B)

F I G. 9

(B)

homogeneous transformation matrix wX_t of position
and attitude of tip point of tool with respect to
the referential point of workpiece at starting time
of manual operations is calculated from eq. (9). ～ S T 1 5

position of referential point of workpiece with respect ～ S T 1 6
to world coordinates system at starting time of manual
operations is calculated from eq. (11), and Euler's
angles are calculated from eqs. (12), (13), (14).

$i = 0$ ～S T 1 7

(E) →

ST 1 8
actuating
signals maintained ? NO

YES

ST 1 9 ～ $i = i + 1$

ST 2 1
all of
actuating signals
0 ? NO

YES

$\Delta t_{-i} = T \times i$ ～ S T 2 0

ST 2 2 ～ END

(D)

(C)

FIG. 10

(D)

positions and Euler's angles of referential point of workpiece with respect to world coordinates system after lapse of time Δt_{-i} are calculated from eq. (15). $\sim ST23$

world X_{w-i} is calculated from eq. (16). $\sim ST24$

homogeneous transformation matrix T_{z-i} of position and attitude of tool handling robot are calculated from eq. (20). $\sim ST25$

homogeneous transformation matrix W_{z-i} of position and attitude of workpiece handling robot are calculated from eq. (22). $\sim ST26$

joint variables of tool handling robot are calculated by inversely transforming T_{z-i}. $\sim ST27$

joint variables of workpiece handling robot are calculated by inversely transforming W_{z-i}. $\sim ST28$

actuating values for actuators based on joint variables of tool handling robot and actuating values for actuators based on joint variables of workpiece handling robot are calculated from eqs. (101) and (102). $\sim ST29$

NO — lapse of time comes into Δt_{-i}? $\sim ST30$

YES

actuating values $a_{t1-i}, a_{t2-i}, \cdots, a_{t6-i}$ for actuators of tool handling robot are outputted, and the actuating values $a_{w1-i}, a_{w2-i}, \cdots, a_{w6-i}$ for actuators of workpiece handling robot are outputted. $\sim ST31$

(E)

F I G. 11

(a)

(b)

(c)

F I G. 12

F I G. 13

FIG. 14

(F)

velocities $V1_w$ $V2_w$ $V3_w$ $V4_w$ $V5_w$ $V6_w$ for each axis manual operation of workpiece handling robot are calculated by use of eq. (23). ⟋ST32

joint variables ϕ_{1-0} ϕ_{2-0} ϕ_{3-0} ϕ_{4-0} ϕ_{5-0} ϕ_{6-0} of workpiece handling robot at starting time of manual operation are inputted. ⟋ST33

joint variables θ_{1-0} θ_{2-0} θ_{3-0} θ_{4-0} θ_{5-0} θ_{6-0} of tool handling robot at starting time of manual operation are inputted. ⟋ST34

homogeneous transformation matrix "world X_{w-0}" of position and attitude of workpiece with respect to world coordinates system at starting time of manual poerations is calculated from eq. (6A). ⟋ST35

homogeneous transformation matrix "world X_{t-0}" of position and attitude of tool with respect to world coordinates system at starting time of manual operations is calculated from eq. (7A). ⟋ST36

homogeneous transfotmation matrix wX_t of position and attitude of tip point of tool with respect to referential point of workpiece at starting time of manual operations is calculated from eq. (9A). ⟋ST37

$i = 0$ ⟋ST38

(G)

FIG. 15

FIG. 16

(H)

---

joint variables ϕ_{1-i} ϕ_{2-i} ϕ_{3-i} ϕ_{4-i} ϕ_{5-i} ϕ_{6-i} of workpiece handling robot after lapse of time Δt_{-i} are calculated from eq. (24). ~ST44

---

homogeneous transformation matrix W_{2-i} of position and attitude of workpiece handling robot is calculated from eq.(26). ~ST45

---

homogeneous transformation matrix T_{2-i} of position and attitude of tool handling robot is calculated from eq. (31) ~ST46

---

joint variables of tool handling robot are calculated by inversely transforming T_{2-i}. ~ST47

---

actuating values for actuators based on joint variables of tool handling robot and actuating values for actuators based on joint variables of workpiece handling robot are calculated from eq. (101) and (102). ~ST48

NO

lapse of time comes into Δt_{-i} ? ~ST49

YES

---

actuating values a_{t1-i}, a_{t2-i}, $\cdots$, a_{t6-i} for actuators of tool handling robot are outputted, and the actuating values a_{w1-i}, a_{w2-i}, $\cdots$, a_{w6-i} for actuators of workpiece handling robot are outputted. ~ST50

(I)

44

FIG. 17

J

robot changing switch 7 on ? ~ST52

YES (workpiece handling robot)

NO (tool handling robot)

velocities $V1_t$, $V2_t$, $V3_t$, $V4_t$, $V5_t$, $V6_t$ for each axis manual operation of tool handling robot are calculated by use of eq. (32). ~ST53

joint variables θ_{1-0}, θ_{2-0}, θ_{3-0}, θ_{4-0}, θ_{5-0}, θ_{6-0} of tool handling robot at starting time of manual operation are inputted. ~ST54

$i = 0$ ~ST55

K

velocities $V1_w$, $V2_w$, $V3_w$, $V4_w$, $V5_w$, $V6_w$ for each axis manual operation of workpiece handling robot are calculated by use of eq. (23C). ~ST65

joint variables ϕ_{1-0}, ϕ_{2-0}, ϕ_{3-0}, ϕ_{4-0}, ϕ_{5-0}, ϕ_{6-0} of workpiece handling robot at starting time of manual operation are inputted. ~ST66

$i = 0$ ~ST67

L

FIG. 18

(K)

ST56 — actuating signals maintained ?

YES

$i = i + 1$ ~ST57

$\Delta t_{-i} = T \times i$ ~ST58

joint variables of tool handling robot are calculated from eq.(33). ~ST61

actuating values for actuators are calculated from joint variables of tool handling robot by ues of eq. (101B). ~ST62

NO — lapse of time comes into Δt_{-i} ? ~ST63

YES

actuating values a_{t1-i} a_{t2-i}, $\cdots$, a_{t6-i} for actuators of tool handling robot are outputted. ~ST64

NO — ST56

~ST59 — all of actuating signals 0 ? — NO

YES

(C)

END ~ST60

FIG. 19

ST68
actuating
signals maintained ?
NO

YES

i = i + 1   ST69

$\Delta t_{-i} = T \times i$ ST70

joint variables of workpiece
handling robot are calculated
from eq. (33C).   ST73

actuating values for actuators are
calculated from joint variables of
workpiece handling robot by use of
eq. (102C).   ST74

ST75
lapse of
time comes into
Δt_{-i} ?
NO

YES

actuating values a_{w1-i}, a_{w2-i}, · · ·,
a_{w6-i} for actuators of workpiece handling
robot are outputted.   ST76

ST71
all of
actuating signals
0 ?
NO

YES

END   ST72

C

L

FIG. 20

(M)

robot
changing switch 7
on ? ~ST82

YES (workpiece handling robot)

NO (tool handling robot)

(O)

velocities V_{xt} V_{yt} V_{zt} $V_{\alpha t}$ $V_{\gamma t}$ for cartesian coordinates manual operation of tool are calculated by use of eq. (35). ~ST83

joint variables θ_{1-0} θ_{2-0} θ_{3-0} θ_{4-0} θ_{5-0} θ_{6-0} of tool handling robot at starting time of manual operation are inputted. ~ST84

homogeneous transformation matrix "world X_{t-0}" of position and attitude of tip point of tool with respect to world coordinates system at starting time of manual operations is calculated from eq. (36). ~ST85

position of tool with respect to world coordinates system at starting time of manual operations is calculated from eq. (38), and Euler's angles are calculated from eqs. (39), (40), (41). ~ST86

$i = 0$ ~ST87

(N)

FIG. 21

FIG. 22

○

ST100

6
degree of freedom ? NO

YES

ST103

velocities $V x_w$ $V y_w$ $V z_w$ $V \alpha_w$ $V \beta_w$ $V \gamma_w$ for cartesian coordinates manual operation of workpiece are calculated by use of eq. (45).

ST101

error message is indicated

joint variables ϕ_{1-o} ϕ_{2-o} ϕ_{3-o} ϕ_{4-o} ϕ_{5-o} ϕ_{6-o} of workpiece handling robot at starting time of manual operation are inputted. ST104

END ST102

homogeneous transformation matrix "world X_{w-o}" of position and attitude of referential point of workpiece with respect to world coordinates system at starting time of manual operations is calculated from eq. (46). ST105

position of workpiece with respect to world coordinates system at starting time of manual operations is calculated from eq. (48), and Euler's angles are calculated from eqs. (49), (50), (51). ST106

i = 0 ST107

Ⓟ

50

F I G. 2 3

F I G. 24

(a)

(b)

(c)

(d)

(54) A manual teaching control device for operations in an industrial robots-system.

(57) According to a control teaching device, position and attitude of tool (2n) on tool handling robot (2) can be taught by means of manual operations, being subjected to the movement of position and attitude of workpiece (1m) on workpiece handling robot (1), so that relative position and attitude of tool (2n) against workpiece (1m) can be kept constant. Position and attitude of workpiece handling robot (1) and tool handling robot (2) are computed by use of "actuating signals" of a teaching key means (12) and a "co-acting signal" of a selecting means for sole-action/co-action (9) . Then, joint variables of workpiece handling robot (1) and tool handling robot (2) are calculated. Actuating values for actuators (17W, 17T) of workpiece handling robot (1) and tool handling robot (2) are synchronously outputted after the lapse of time comes into a predetermined infinitesimal time ΔT, therefore, tool (2n) is synchronously co-acted with workpiece (1m).

FIG. 1

EP 0 521 440 A3

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int. Cl.5)

DOCUMENTS CONSIDERED TO BE RELEVANT — EP 92111015.1

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int. Cl.5)
X	US - A - 5 020 001 (YAMAMOTO) * Figs. 1-6; abstract; columns 4-6; claims * --	1-3	B 25 J 9/16
X	EP - A - 0 177 142 (CINCINNATI MILACRON) * Figs.; abstract; claims * --	1-3	
X	WO - A - 91/04 522 (AITEC OY/HAIPUS) * Figs. 1-4; abstract; page 4, line 29 - page 7, line 21 * --	1-3	
X	GB - A - 2 208 553 (RENISHAW PLC) * Figs. 3,4; abstract; page 6, lines 1-31 *	1	
A	* Figs. 1-4 * ----	2,3	

TECHNICAL FIELDS SEARCHED (Int. Cl.5)

B 25 J 9/00
G 05 B 19/00

The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
VIENNA	29-06-1993	KRAL